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R. Andrew Goodwin, Ph.D.

U.S. Army Engineer Research and Development Center
333 SW 1st Avenue
Portland, OR 97208

John M. Nestler, Ph.D., Toni Toney

Environmental Laboratory
U.S. Army Engineer Research and Development Center
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

James J. Anderson, Ph.D.

School of Aquatic and Fishery Sciences, Columbia Basin Research
University of Washington
1325 4th Avenue, Suite 1820
Seattle, WA 98101

Jina Kim

BAE Systems, Fisheries Engineering Team
40 S.E. Cascade Avenue
Stevenson, WA 98648

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ABSTRACT: As part of the Federal Energy Regulatory Commission (FERC) relicensing process, Public Utility District No. 2 of Grant County (the District) wishes to improve performance of fish bypass at Wanapum Dam. The Numerical Fish Surrogate (NFS) is a Eulerian-Lagrangian-agent model (ELAM) developed for analyzing, decoding, and forecasting the movement and passage behavior response of outmigrating juvenile salmon (migrants) in complex 3-D hydrodynamic fields near fish bypass systems in hydropower dam forebays. The NFS (and ELAMs, in general) uses a mechanistic "plug-and-play" behavior algorithm embodying a biological hypothesis of how an individual responds to biotic and/or abiotic stimuli.

The University of Iowa IIHR - Hydroscience and Engineering developed a computational fluid dynamics (CFD) model to describe the 3-D steady-state hydrodynamic fields associated with 12 different structural and operational fish bypass system configurations (cases) at Wanapum Dam. In Phase 1 of the study, forecast (virtual fish) and observed (radio-tagged fish) passage proportions were compared for five different cases from years 1997, 2001, and 2002. Comparison of forecast and observed passage for four out of the five cases were done blindly (i.e., independently reviewed and evaluated) and within the expected limits of about 5 to 10 percent for the bypass systems and considerably better than forecasts of passage from passive particles (i.e., behavior rules turned off). This indicates migrant movement behavior in the flow field is likely an integral part of bypass success. In Phase 2 of the study, the NFS was used to forecast the passage response of migrants to seven different structural and operational design alternatives under consideration for Wanapum Dam prior to construction and installation.

Results indicate the NFS is a viable technology for use at Wanapum Dam to assess different fish bypass design alternatives. NFS performance is limited by (a) the robustness of the underlying mechanistic biological hypothesis, (b) accuracy and resolution of the CFD modeled hydrodynamics, and (c) accuracy and robustness of the observed (radio-tagged fish) passage proportions for describing the passage response of a target species or population. Concurrence between forecast and observed passage proportions supports the Strain-Velocity-Pressure (SVP) Hypothesis as an approximation of the strategy used by migrants to hydraulically navigate through complex flow fields. The NFS may be used to reduce uncertainty and, therefore, the cost and impact on migrants, in the process of designing and operating bypasses. NFS accuracy is expected to improve with additional observed data and model calibration.

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Preface

Public Utility District No. 2 of Grant County (the District) operates Wanapum Dam in the Mid-Columbia River to generate hydropower and for other beneficial purposes as allowed by their Federal Energy Regulatory Commission (FERC) license. As part of the FERC relicensing procedure, the District wishes to improve performance of fish bypass at Wanapum Dam. The District has conducted prototype fish passage evaluations during controlled plant operations at which time radio-tagged fish were used to index passage percentages at different reservoir exits. These data are used to better understand the performance of different bypass system designs and can be used to help calibrate a three-dimensional (3-D) fish movement behavior decision-support tool that can forecast bypass system performance. The University of Iowa IIHR - Hydroscience and Engineering provides design and operations support to develop concepts for improving fish bypass at Wanapum Dam. The IIHR requested assistance from the U.S. Army Engineer Research and Development Center (ERDC) to evaluate performance of alternative fish bypass system designs for Wanapum Dam using the Numerical Fish Surrogate (NFS) under Cooperative Research and Development Agreement 02-EL-05. The NFS is a system of computer programs for analyzing, decoding, and forecasting detailed 3-D movement and passage response behavior patterns of aquatic species (e.g., outmigrating juvenile salmon) in complex 3-D hydrodynamic fields typical of bypass systems. Tests and resulting data herein, unless otherwise noted, were obtained from research conducted under sponsorship of the University of Iowa, Iowa City, Iowa.

This report was prepared by the Environmental Laboratory (EL), ERDC, Vicksburg, MS. This report was written by Dr. R. Andrew Goodwin and Dr. John M. Nestler, EL, and Dr. James J. Anderson, University of Washington, under the direct supervision of Dr. Barry Bunch, Chief, Water Quality and Contaminant Modeling Branch (WQCMB), EL, and under the general supervision of Dr. Richard E. Price, Chief, Ecosystem Processes and Effects Division, EL, and Dr. Edwin Theriot, Chief, EL. Ms. Jina Kim of the Fisheries Engineering Team, BAE Systems, Stevenson, WA, processed data and helped run the NFS model. Ms. Toni Toney, WQCMB, ran NFS analyses, processed and assessed results, and helped prepare the report. A technical review was performed by Dr. Songheng Li of the University of Iowa IIHR – Hydroscience and Engineering and Ms. Dorothy Tillman, WQCMB. Ms. Tracey Hopkins, WQCMB, assisted in the preparation of this report.

The methods described in this report to forecast the movement and passage response behavior of juvenile salmon are protected by Patent number 6,160,759 entitled “Method for Determining Probable Response of Aquatic Species to Selected Components of Water Flow Fields.”

At the time of publication of this report, COL James R. Rowan, EN, was Commander and Executive Director of ERDC. Dr. James R. Houston was Director.

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1 Introduction

Background

Public Utility District No. 2 of Grant County (the District) operates Wanapum Dam in the Mid-Columbia River to generate hydropower and for other beneficial purposes as allowed by their Federal Energy Regulatory Commission (FERC) license. As part of the FERC relicensing procedure, the District wishes to significantly improve performance of the fish bypass system at Wanapum Dam. The District has conducted prototype fish passage evaluations during controlled plant operations at which time radio-tagged fish were used to index passage percentages at different reservoir exits. These data are used to better understand the performance of different bypass system designs and could be used to calibrate a three-dimensional (3-D) fish movement behavior decision-support tool that can forecast bypass system performance. The University of Iowa IIHR - Hydroscience and Engineering (IIHR) provides design and operations support to develop concepts for improving fish bypass at Wanapum Dam. The IIHR requested assistance from the U.S. Army Engineer Research and Development Center (ERDC) to evaluate performance of alternative fish bypass system designs for Wanapum Dam using the Numerical Fish Surrogate (NFS) under Cooperative Research and Development Agreement 02-EL-05. The NFS is a system of computer programs for analyzing, decoding, and forecasting detailed 3-D movement behavior of aquatic species (e.g., outmigrating juvenile salmon) in complex 3-D hydrodynamic fields typical of bypass systems.

The study was conducted in two phases. For Phase 1, IIHR provided summary passage data only for the Mandatory Operating Agreement (MOA) spill (Case 2002_MOA) for preliminary inspection and calibration (if necessary). After an adequate fit was confirmed to this scenario by ERDC, then the NFS model was blindly applied to an additional four scenarios provided by IIHR. The results of the additional four scenarios were provided to IIHR for independent review and evaluation of the performance of the NFS. ERDC was given approval for Phase 2 studies after IIHR and the District deemed NFS performance adequate. Phase 2 studies included more detailed NFS output and analysis of the initial five cases of Phase 1 and an evaluation of an additional seven scenarios provided by IIHR. This report describes results from both investigation phases.

Objectives

This report documents Phase 1 and Phase 2 application of the NFS with objectives as follows:

Phase 1: provide forecasts of fish passage percentages of outmigrating juvenile salmon at Wanapum Dam under five conditions: (a) attraction flow prototype (AFP) (Case 1997_AFP), (b) ice-trash sluiceway (Case 2001), (c) bulkhead spill with training flow (combined spill) (Case 2002_Mixed), (d) MOA spill (Case 2002_MOA), and (e) top spill bulkhead (Case 2002_TopSpill).

Phase 2: provide summary forecasted passage percentages and ancillary information for each outlet from the dam for operation/design alternatives selected by the District and supported by Computational Fluid Dynamics (CFD) analyses. The cases involved in this phase include the initial five cases of Phase 1 and an additional seven fish bypass alternatives. The seven alternatives are: (a) concept 10 at future unit 10 with 5 kcfs bypass flow (Case Cncpt10_5K), (b) concept 10 at future unit 10 with 10 kcfs bypass flow (Case Cncpt10_10K), (c) concept 10 at future unit 10 with 20 kcfs bypass flow (Case Cncpt10_20K), (d) concept 11 at future unit 11 with 5 kcfs bypass flow (Case Cncpt11_5K), (e) concept 11 at future unit 11 with 10 kcfs bypass flow (Case Cncpt11_10K), (f) concept 11 at future unit 11 with 20 kcfs bypass flow (Case Cncpt11_20K), and (g) top spill bulkhead with 20 kcfs bypass flow (Case TSB_AFP).

2 Methods

The NFS is a Eulerian-Lagrangian-agent model, or ELAM (Goodwin et al. 2004a, 2004b, 2004c; Goodwin 2004), developed by R. Andrew Goodwin and John Nestler of ERDC with Jim Anderson (University of Washington, School of Aquatic and Fishery Sciences) and Larry Weber (University of Iowa IIHR – Hydroscience and Engineering). The NFS implements and extends ideas first proposed by Anderson (1988) by integrating detailed biological, behavioral, movement, and hydraulic information into a common, unified mathematical and computer framework for 3-D analysis, decoding, and simulation of fish movement and passage behavior. Information from field telemetry and monitoring data is used to develop and refine mechanistic behavior rules that embody a fish behavior hypothesis. These rules are programmed into a particle-tracker so that particles can respond to information provided to them by CFD output – that is, they become “smart” particles. We consider each particle to be surrounded by a sensory ovoid (radius of 1-2 m) from within which the particle acquires information about hydraulic gradients. These gradients become inputs to the behavioral rules. The behavior rule outputs swim vectors that are added to the passive transport vectors to obtain new positions at subsequent time steps. Using this strategy allows the NFS to become a “plug-and-play” fish simulator where specific behavior hypotheses can be objectively and quantitatively evaluated. The NFS presently employs the Strain-Velocity-Pressure (SVP) Hypothesis (Goodwin et al. 2004a; Goodwin 2004) to simulate the movement and passage behavior of outmigrating juvenile salmon in the forebays of mainstem Columbia and Snake River hydropower dams, as described later. The SVP hypothesis is able to explain complex patterns in fish passage at Lower Granite Dam and has been successfully tested against a total of eleven separate design/operational alternatives. The NFS is protected by U.S. Patent Number 6,160,759 awarded on 12 December 2000, entitled “Method for Determining Probable Response of Aquatic Species to Selected Components of Water Flow Fields.”

Data Sources and Handling

The NFS, in conjunction with the output of high-resolution CFD modeled data, creates a mathematical representation of a hydropower dam forebay with sufficient fidelity to the real world that fish bypass designs and operations can be accurately assessed. The data needs and conventions used to create this virtual reality are described below.

a. Hydrodynamic data. The five Phase 1 scenarios and seven Phase 2 scenarios for which CFD model hydrodynamic data were developed are described in Table 1 and Table 2, respectively. The hydrodynamic fields for each condition were provided by IIHR. Hydrodynamic model description, operation, and scenario conventions are documented in Li and Weber (2004a, 2004b).

Table 1
Phase 1 Five Test Cases: Comparison of Flow Conditions and Observed/Forecasted Fish Passage for Wanapum Dam

Structure Type	CFD Flow, kcfs	Observed Passage, %[1]	Forecasted Passage, % 5,000 fish	*(2,000 fish)*	[5,000 passive particles]
Case 1997_AFP: Bypass structure is AFP channel					
Bypass Structure	1.4	1.0	**0.0**	*(0.1)*	[0.4]
Sluice Gate	2.2	2.0	**2.9**	*(2.9)*	[0.1]
Turbines	151.2	36.0	**48.9**	*(46.1)*	[34.6]
Spillway	99.9	61.0	**42.7**	*(42.0)*	[49.2]
In Forebay			**5.5**	*(8.9)*	[15.8]
Case 2001: Bypass structure is sluice gate					
Bypass Structure	-	-	**-**	-	-
Sluice Gate	1.7	40.2	**29.1**	*(27.5)*	[1.8]
Turbines	42.8	32.3	**58.5**	*(45.6)*	[40.1]
Spillway	21.6	24.5	**5.3**	*(3.5)*	[42.4]
In Forebay			**7.2**	*(23.5)*	[15.7]
Case 2002_Mixed: Bypass structure is bulkhead top spill at spillbay 12					
Bypass Structure	11.9	26.7	**22.8**	*(21.9)*	[11.1]
Sluice Gate	-	-	**-**	-	-
Turbines	107.1	56.6	**60.9**	*(56)*	[47.0]
Spillway	22.6	14.7	**8.9**	*(8.2)*	[25.5]
In Forebay			**7.4**	*(13.9)*	[16.4]
Case 2002_MOA: Bypass structure is sluice gate					
Bypass Structure	-	-	**-**	-	-
Sluice Gate	1.9	6.9	**6.7**	*(7.6)*	[0.7]
Turbines	91.9	58.4	**50.3**	*(49.2)*	[37.0]
Spillway	52.5	33.7	**31.9**	*(29.8)*	[46.6]
In Forebay			**11.1**	*(13.4)*	[15.8]
Case 2002_TopSpill: Bypass structure is bulkhead top spill at spillbay 12					
Bypass Structure	12.2	17.9	**14.3**	*(13.2)*	[14.7]
Sluice Gate	-	-	**-**	-	-
Turbines	134.6	91.1	**78.0**	*(73.3)*	[68.4]
Spillway	0.0	0.0	**0.0**	*(0.0)*	[0.0]
In Forebay			**7.5**	*(13.4)*	[16.8]

[1] Observed (radio-tagged fish) passage percentages from LGL Limited (2005).

Table 2
Phase 2 Seven Forecast Cases: Comparison of Flow Conditions and Forecasted Fish Passage for Wanapum Dam

Structure Type	CFD Flow, kcfs	Observed Passage, %	Forecasted Passage, % 5,000 fish
Case Cncpt10_5K: Bypass structure at future unit 10			
Bypass Structure	5.0	N/A	**17.3**
Sluice Gate	0.0	N/A	**0.0**
Turbines	130.0	N/A	**78.7**
Spillway	0.0	N/A	**0.0**
In Forebay		N/A	**4.0**
Case Cncpt10_10K: Bypass structure at future unit 10			
Bypass Structure	10.0	N/A	**17.2**
Sluice Gate	0.0	N/A	**0.0**
Turbines	125.0	N/A	**77.8**
Spillway	0.0	N/A	**0.0**
In Forebay		N/A	**5.0**
Case Cncpt10_20K: Bypass structure at future unit 10			
Bypass Structure	20.0	N/A	**25.4**
Sluice Gate	0.0	N/A	**0.0**
Turbines	115.0	N/A	**69.2**
Spillway	0.0	N/A	**0.0**
In Forebay		N/A	**5.5**
Case Cncpt11_5K: Bypass structure at future unit 11			
Bypass Structure	5.0	N/A	**15.4**
Sluice Gate	0.0	N/A	**0.0**
Turbines	130.0	N/A	**79.1**
Spillway	0.0	N/A	**0.0**
In Forebay		N/A	**5.5**
Case Cncpt11_10K: Bypass structure at future unit 11			
Bypass Structure	10.0	N/A	**17.7**
Sluice Gate	0.0	N/A	**0.0**
Turbines	125.0	N/A	**76.5**
Spillway	0.0	N/A	**0.0**
In Forebay		N/A	**5.8**
Case Cncpt11_20K: Bypass structure at future unit 11			
Bypass Structure	20.0	N/A	**25.4**
Sluice Gate	0.0	N/A	**0.0**
Turbines	115.0	N/A	**68.4**
Spillway	0.0	N/A	**0.0**
In Forebay		N/A	**6.2**

(Continued)

Table 2 (Concluded)			
Structure Type	**CFD Flow, kcfs**	**Observed Passage, %**	**Forecasted Passage, % 5,000 fish**
Case TSB_AFP: Bypass structure (bulkhead top spill) at spillbay 12			
Bypass Structure	20.0	N/A	**22.5**
Sluice Gate	0.0	N/A	**0.0**
Turbines	115.0	N/A	**73.3**
Spillway	0.0	N/A	**0.0**
In Forebay		N/A	**4.2**

b. *Passage percentage data*. Measured fish passage percentages pooled by exit (total powerhouse, total spillway, and total bypass) were provided sequentially in summary form by IIHR consistent with the phased structure of the study. Significant features of the observed passage data include:

(1) Passage distribution is based on radio-tagged hatchery-reared Chinook smolts (LGL Limited 2005).

(2) All smolts were released about 6.4 km (4 miles) upstream of Wanapum Dam near Vantage Bridge.

(3) Small percentages of fish were dipped from the gate wells and are incorporated into powerhouse passage.

c. *Behavior model parameterization*. We imported coefficients initially developed to simulate passage at Lower Granite Dam for use at Wanapum Dam. No modifications were made to these coefficients even though hatchery steelhead passage dominates at Lower Granite Dam whereas hatchery yearling Chinook salmon passage dominates at Wanapum Dam. We were not provided any data on turbine- or spillbay-specific passage nor were we provided 3-D telemetry (e.g., acoustic-tag traces) of fish movement.

d. *Lateral release distribution of virtual fish*. Sensitivity analysis of the NFS shows that lateral and depth distributions of virtual fish release locations can significantly affect NFS model performance. Unfortunately, lateral and depth distribution data are unavailable for juvenile salmon upstream of Wanapum Dam. We performed the analysis using both a 50 and an 80 percent lateral distribution to accommodate for the lack of distribution data (depicted in Figure 1) to determine if there is a significant effect on NFS model output. In the 50 percent lateral distribution, virtual fish are released in the middle centered 50 percent of the total width of the river cross section, and, in the 80 percent lateral distribution, virtual fish are released in the middle centered 80 percent of the total width of the river cross section.

e. *Vertical release distribution of virtual fish*. Three different vertical distributions for virtual fish are used: day, night, and composite (an even blending of day and night distributions). Diel vertical fish distribution data are not available for outmigrating juvenile salmon entering the

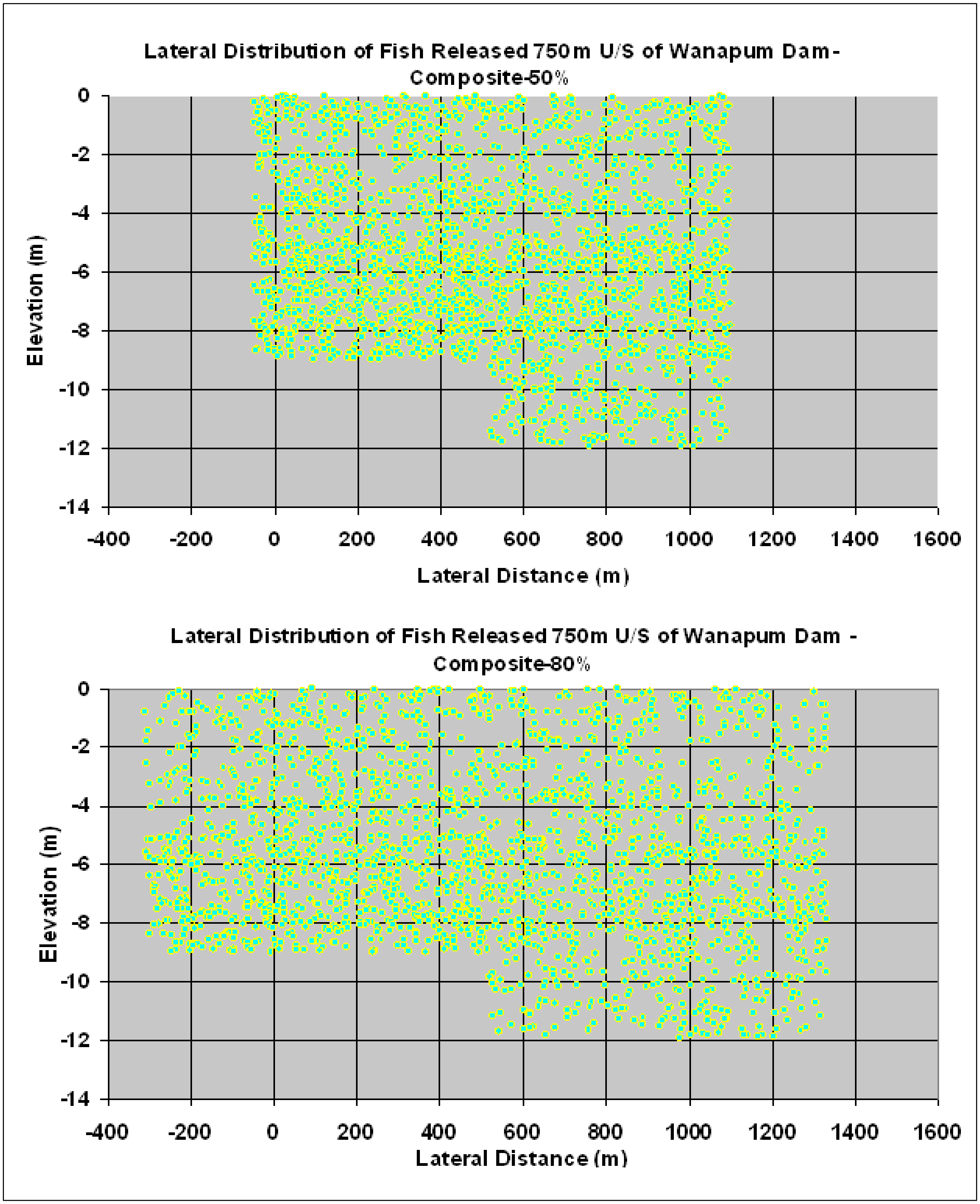

Figure 1. Comparison of 50 percent and 80 percent lateral release distributions for virtual fish used in the NFS model analysis. Depth distributions were similar between 50 percent and 80 percent lateral release distributions. Water surface is at elevation 0 m

Wanapum forebay. Therefore, vertical release distributions were based on similar data developed for Lower Granite Dam (Johnson and Kim 2004). A comparison of day versus night vertical distributions for the 80 percent lateral distribution is shown in Figure 2. We present results for all three vertical release distributions, but generally focus on the composite vertical and 80 percent lateral distribution.

f. *Longitudinal distance from dam for release of virtual fish*. Ideally, virtual fish should be released close to the upstream boundary of the CFD model mesh. However, there is a tradeoff between computer run time and upstream release distance because, just as in the real world, virtual fish released farther upstream require more time to pass through the forebay and into the dam which increases run time. For Wanapum Dam NFS analyses, an acceptable compromise between run time and sufficient virtual fish passing the dam is believed to exist when virtual fish are released approximately 750 m upstream of the dam (Figure 3).

g. *NFS model run duration, number of released virtual fish, and computational resources*. The NFS is a computationally demanding mathematical model. The NFS is run on U.S. Army Major Shared Resource Center supercomputers. The computational infrastructure of the NFS (as of June 2004) limited NFS simulations of 5,000 virtual fish to approximately 11 hr of virtual fish time (20,000 2-sec time steps). Simulations took several hours. As of January 2005, the NFS can be run on unstructured CFD model meshes with substantially longer virtual fish run times and in far less user time, can simulate more virtual fish, and is in the process of being parallelized to maximize computational efficiency.

Linking Hydrodynamic Pattern and Outmigrating Juvenile Salmon Movement Behavior

Conceptual model

Studies at Lower Granite Dam have provided sufficient insight into outmigrating juvenile salmon (migrant) movement behavior to develop a conceptual model for migrant swim path selection. The conceptual model, termed the SVP Hypothesis for its primary components of hydraulic strain, water velocity, and pressure (or its surrogate depth) is described below. The SVP Hypothesis explains how a migrant is able to create an "image" of the physical boundaries of a river channel in the complete absence of light using only hydrodynamic information. More detail about the conceptual model can be found in Goodwin (2004).

Understanding the SVP Hypothesis first requires a basic understanding of fluvial geomorphology. In free-flowing rivers, pattern in a flow field results from flow resistance. Without flow resistance, there is no force that can alter the pattern of bulk flow once it is set into motion by the force of gravity. For subcritical flow, flow resistance can be broadly separated into two categories relative to the scale of a fish of interest: skin resistance (which produces wall-bounded flow) and internal distortion resistance (which produces downstream free-shear flow). The hydrodynamic signatures of these two types of flow resistance are

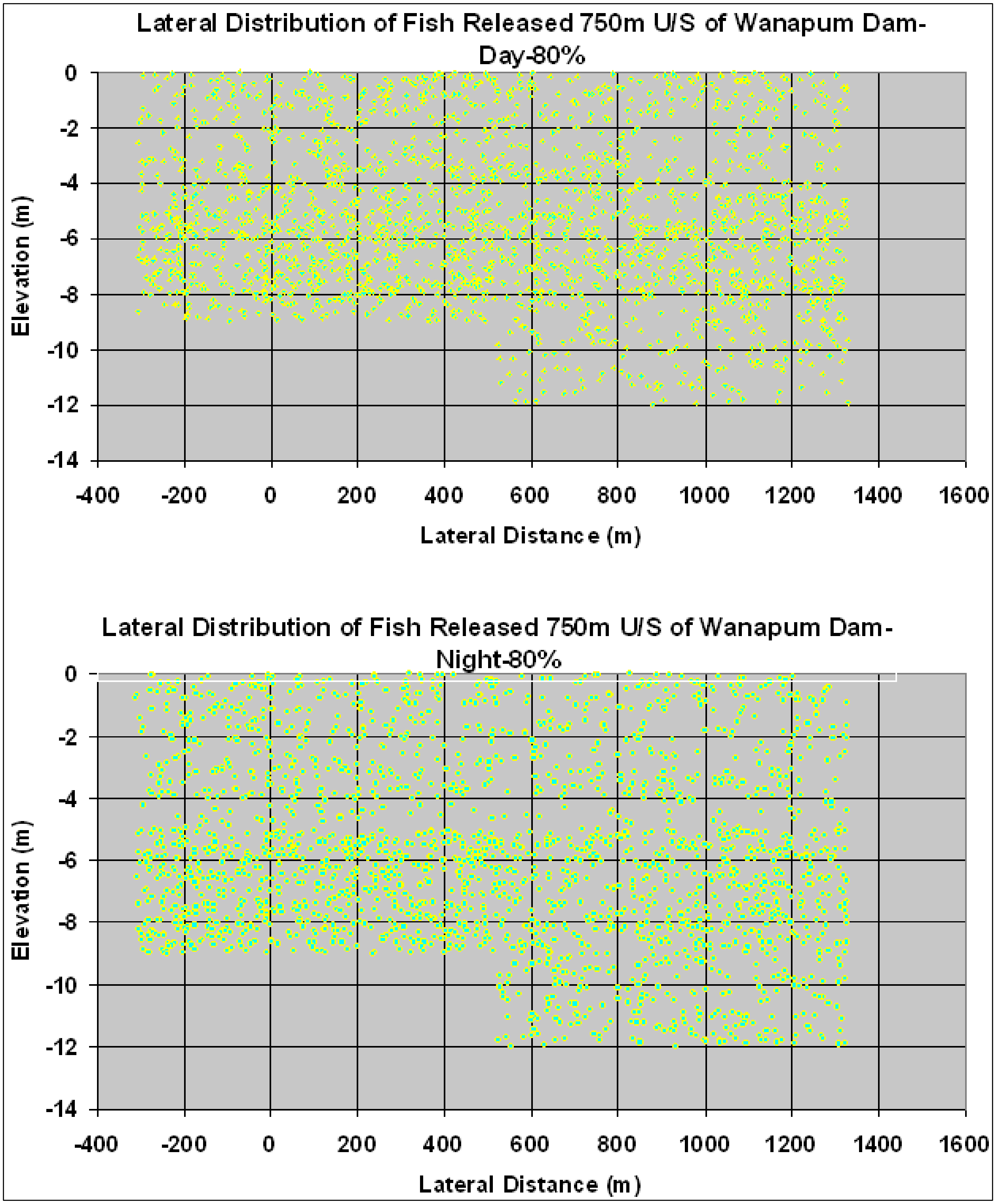

Figure 2. Comparison of day versus night vertical distributions for virtual fish in the 80 percent lateral distribution (Note: fewer night fish are higher in the water column at night. Water surface is at elevation 0 m)

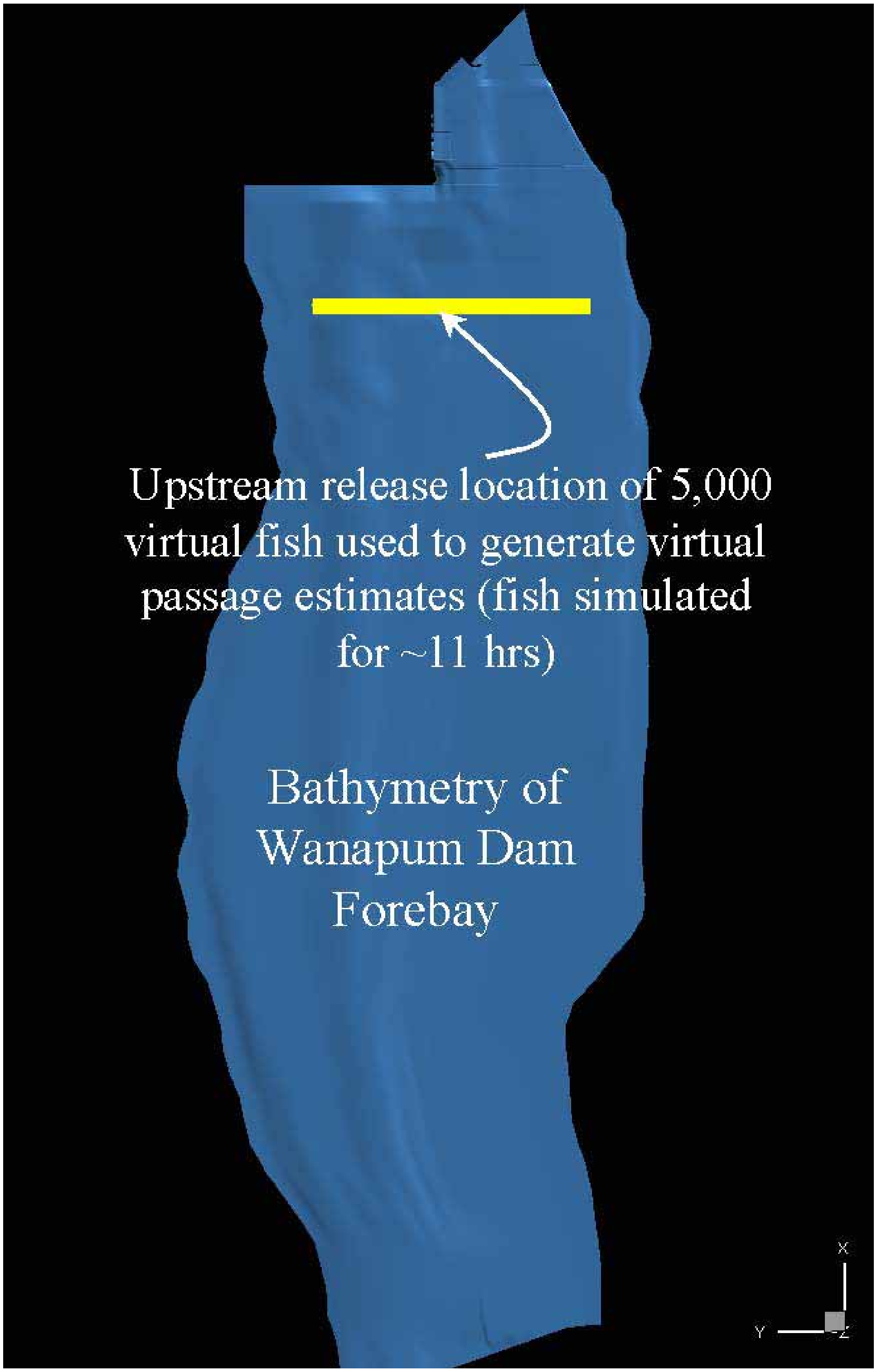

Figure 3. Plan view of CFD model mesh bathymetry boundary and upstream location of virtual fish release distribution (80 percent lateral distribution)

different and, concomitantly, the behaviors they elicit from migrants are also different. This fact is one of the primary reasons why the describing of the "fish-flow relationship" has been so intractable. It also explains why small-scale flume extrapolations of fish behavior to open field scale are often unsuccessful. Fish may respond differently to exactly the same local absolute velocity, depending upon whether it is perceived as being generated by a feature associated with skin resistance or a feature associated with internal distortion resistance or a blend of the two.

The first type of flow resistance is skin resistance. Skin resistance (e.g., bed friction) in a simple, straight, uniform channel produces a general flow pattern in which average velocities are lowest nearest a source of friction (such as the channel bottom and edges) and highest farthest from the friction source (just under the surface in the middle of a symmetric simple channel). A water velocity of zero occurs at the water-solid boundary interface (i.e., the hydraulic "no-slip" condition). The most useful hydraulic variables for understanding migrant behavior are the rates of hydraulic strain (Figure 4) and velocity magnitude. In a simple, straight, uniform channel, a migrant moving toward the channel edge or bottom from a zone of maximum water velocity will experience an increasing strain rate and decreasing water velocity (spatial water deceleration). In contrast, a migrant that moves away from solid boundaries will experience a decrease in the strain rate and a corresponding increase in velocity. By minimizing strain, a migrant can consistently locate itself in the part of this hypothetical river channel exhibiting the greatest mean downstream water velocity (Figure 5). The following two-step rule (based on a strain threshold, k_1, that identifies the signature of a source of skin resistance) allows a migrant to consistently locate itself in the part of a simple, straight, uniform channel that exhibits the greatest average downstream water velocity:

a. Follow the flow until a strain threshold (k_1) is detected.

b. After the strain threshold (k_1) is detected, swim in the direction of greatest velocity.

This simple two-step rule minimizes migration time to the ocean, minimizes bioenergetic cost of migration, and reduces the likelihood of encounters with ambush predators. Of course, the ability of a migrant to detect low strain rates is conditioned by the sensitivity of its sensory system, background strain "noise", and antecedent strain history as described in the next section.

The second type of flow resistance is internal distortion resistance such as large woody debris or rock outcrops. The hydrodynamic signature of internal distortion flow resistance (also referred to as free-shear flow) can also be described in terms of hydraulic strain and water velocity. As in the case of skin resistance, strain rate associated with internal distortion resistance increases toward the signal source. However, in contrast to bed friction (where water velocity decreases toward the source of friction), water velocity increases toward the signal source for internal distortion resistance (Figure 6). Hydraulic strain associated with internal distortion resistance (represented as k_2 where $k_2 > k_1$) results from a local reduction in conveyance area and increased travel distance of water flowing around an obstruction (e.g., flow around a tree limb submerged in

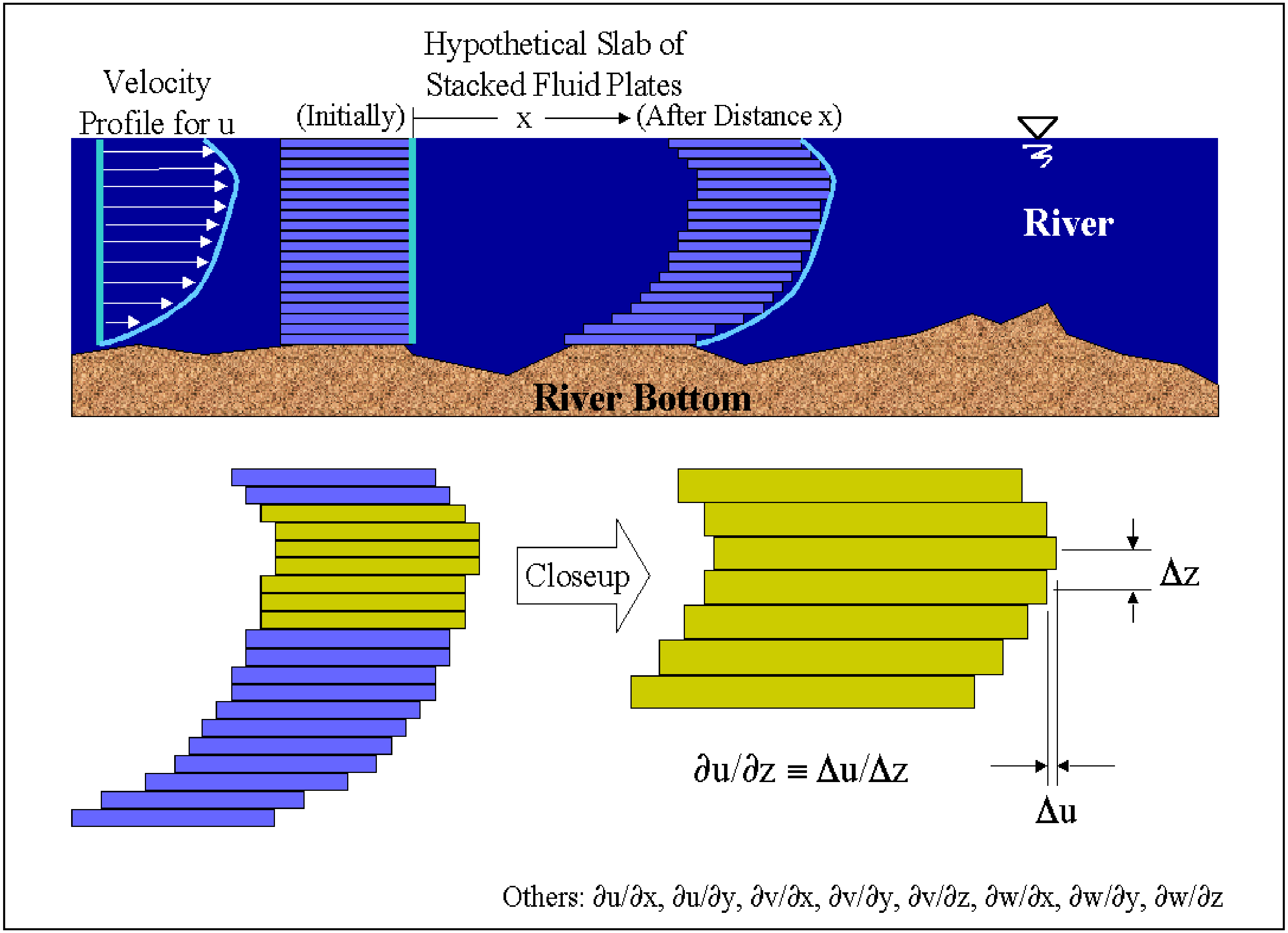

Figure 4. Illustration of one of the nine rates of hydraulic strain

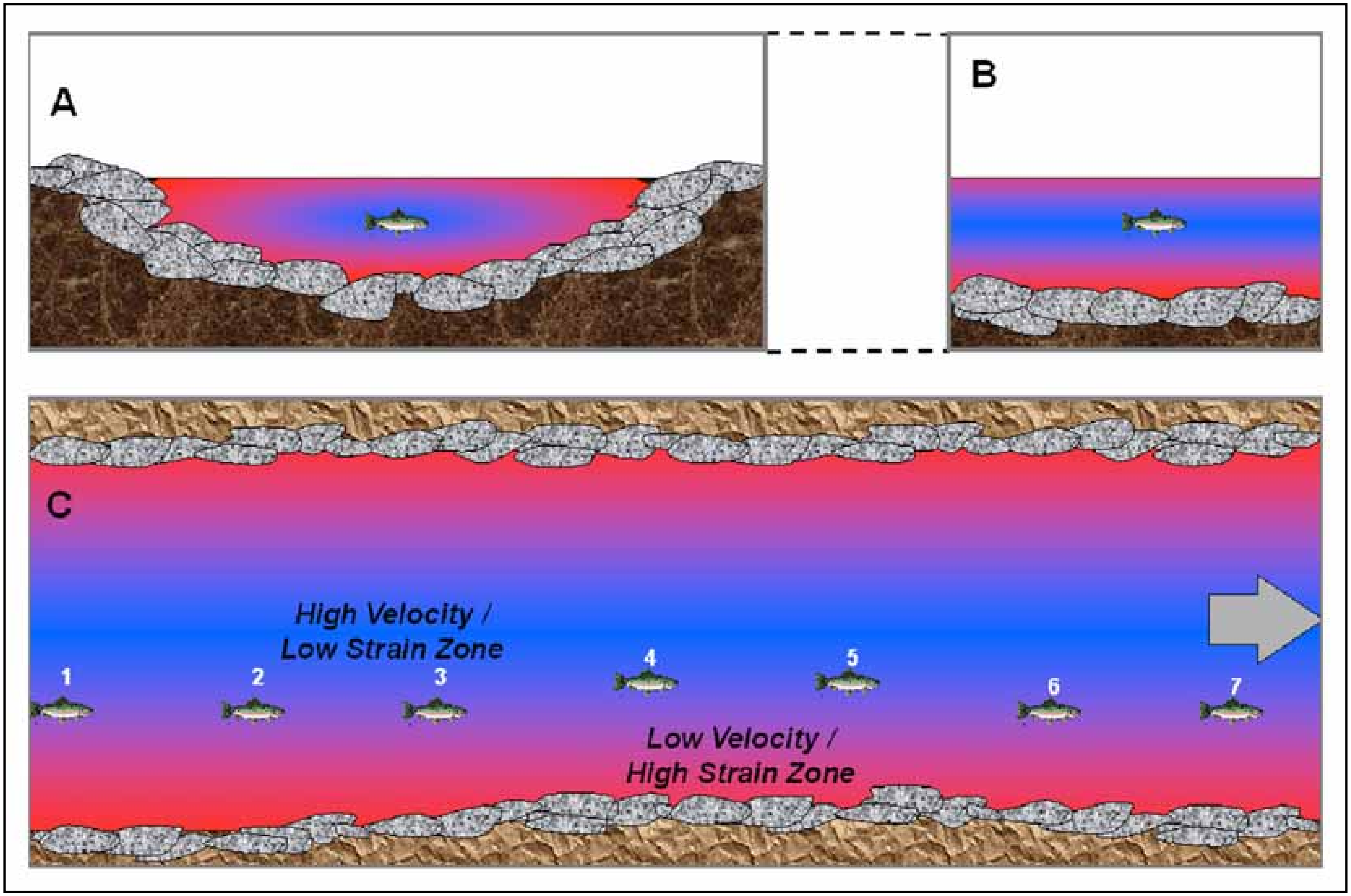

Figure 5. Explaining migrant movement behavior in an environment dominated by skin resistance (wall-bounded flow) in a simple, relatively uniform, straight channel in cross section (A), profile (B), and plan (C) view. Color codes: red = low velocity and high strain and blue = high velocity and low strain (Note: the greatest average downstream velocity, represented by darkest blue, can be consistently located by a migrant using the two-step behavioral rule described in the text. That is, if a fish swims in the direction of greatest velocity whenever it detects the strain threshold k_1, then it will approximately follow the trace of the migrant shown in (C))

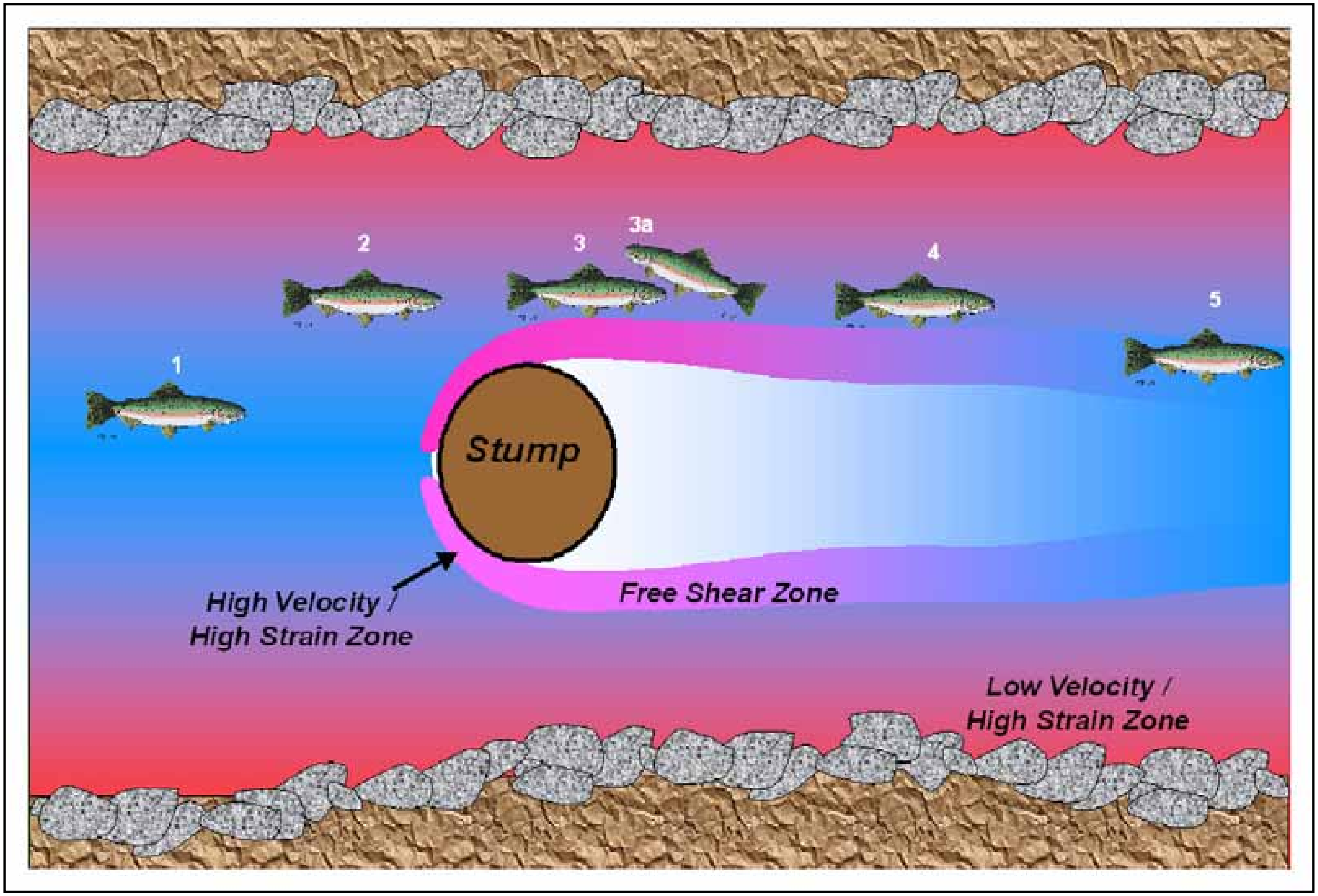

Figure 6. Plan view of schematic river channel explaining migrant movement behavior (locations 1-5) in an environment containing both a source of skin resistance (the shoreline – signaled by the k_1 threshold) and a source of internal distortion resistance (the stump – signaled by the k_2 threshold). By avoiding the free-shear zones in the wake of the stump, a migrant avoids lurking predators and potential turbulence (not shown). We postulate that migrants may reverse their orientation (position 3a versus 3) to more effectively dart away if the free-shear becomes turbulent or if a predator is encountered. By avoiding conditions associated with either the k_1 or k_2 thresholds, a migrant is able to pass through the channel in a way that minimizes the risks of delay, predation, and inefficient swimming conditions

the channel or a protruding rock). The increased velocity resulting from increasing path length is the same as experienced by an air particle traveling faster over the surface of an airplane wing than under the wing. A migrant approaching a tree limb from the upstream direction will detect an increase in strain and an increase in water velocity until solid boundary effects very close to the obstruction are encountered. Once a migrant encounters the signature of a source of internal distortion resistance, it attempts to swim in the direction of decreasing water velocity to minimize exposure to hydraulic strain (Figure 7), which can signal impending turbulence and, thus, loss of sensory acuity and swimming efficiency. If there is no discernable, favorable direction available, then the migrant searches for an interpretable signature, which may result in the migrant reversing its path or milling.

The response of migrants to pressure is determined by the anatomy of its swim bladder. The swim bladder is sensitive to hydrostatic pressure (Coutant 2001) and allows fish to maintain near-neutral buoyancy by adjusting bladder volume (Lucas and Baras 2000). Increases in swim bladder volume in salmonids must occur slowly unless they are near the water surface where air gulping is possible. The Ideal Gas Law, $PV = nRT$ (R = constant), stipulates that for a constant number of molecules of gas, n, within the bladder in an environment of relatively constant temperature, T, bladder volume, V, expands and contracts due to pressure, P. Hydrostatic pressure (proportional to depth) is the dominant pressure constituent suggesting that migrants would be expected to generally change depth at a rate approximately equivalent to their ability to adjust the volume of their swim bladder.

The SVP Hypothesis, when applied to hydraulic patterns commonly observed at dams, accounts for the counter-intuitive migrant behavior often observed by fishery biologists (Figure 6). Completely submerged, 3-D, high-energy intake plumes are common at dams. According to the SVP Hypothesis, a migrant approaching the free-shear zone of an intake will respond as though it has encountered a source of internal distortion resistance typical of a log or rock outcrop. That is, the migrant will swim away from the free-shear zone and toward what it perceives to be a part of the flow field that will carry it more safely around the obstruction (i.e., in a lower velocity zone with less hydraulic strain). Unfortunately, this behavior results in milling and confusion by the migrant, because there is no longer a flow component that will carry a migrant around the virtual obstruction (i.e., intake). We postulate that migrants delay and become confused at dams because some hydrodynamic patterns at dams do not provide affable routes of passage that areas of skin resistance and internal flow resistance in free-flowing rivers offer the evolved inherent behavior of migrants. Flow patterns unique to dams are not geologically persistent and, consequently, salmon have not had the opportunity to evolve appropriate behaviors for them.

Mechanistic model

Mechanistic modeling to guide bypass design requires a quantitative link between environmental patterns and behavior. Creation of useful models for fish passage forecast simulation is confounded by the presence of three separate theoretical approaches for analysis of animal movement and aggregation:

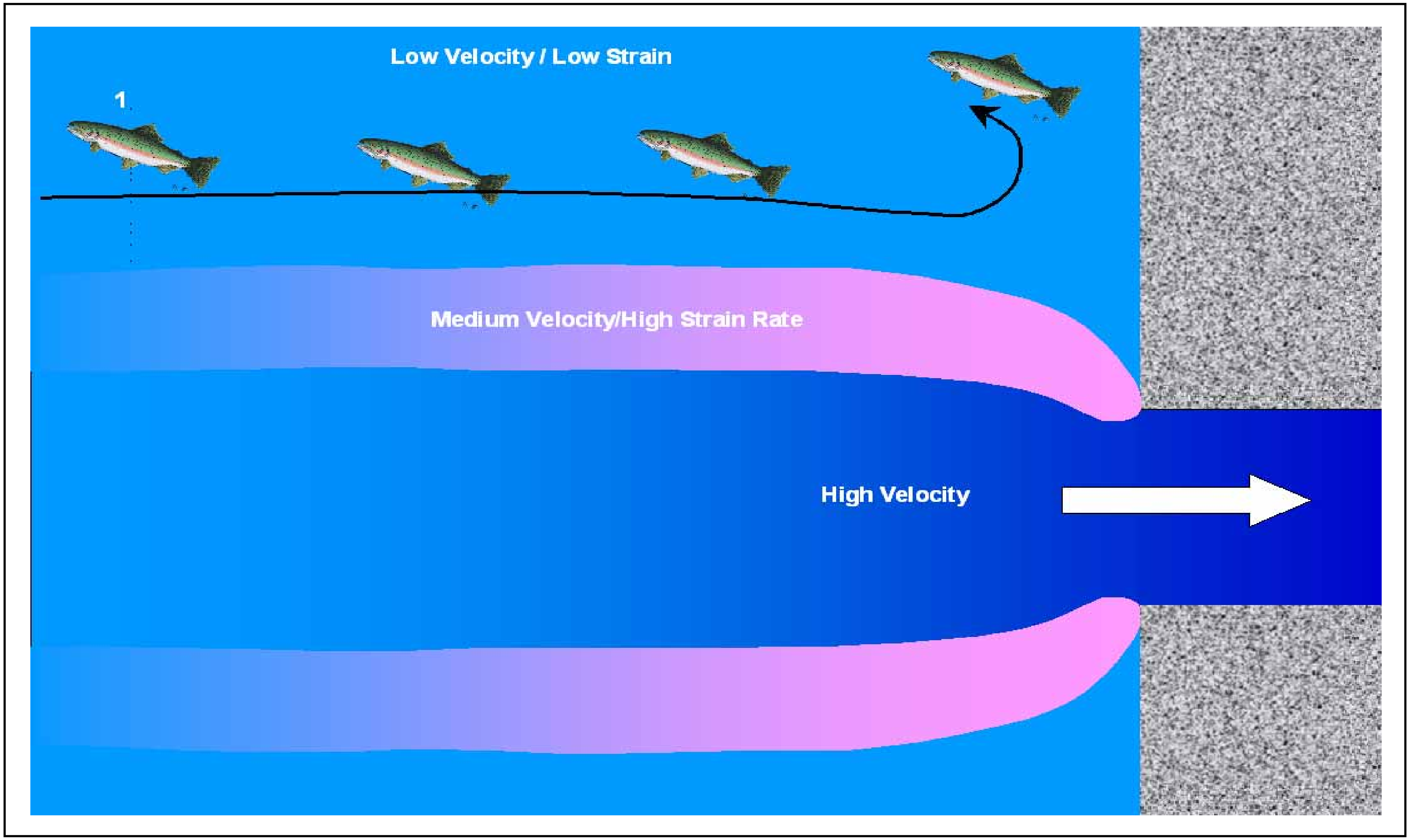

Figure 7. Schematic explaining how a fish may respond to the edges of a submerged, 3-D, high-energy intake plume common at dams, but very unusual in deep, natural, free-flowing rivers. We postulate that a migrant approaching this feature from the side will interpret it as the free-shear zone associated with a source of internal distortion resistance and avoid it. As in a stream, it will attempt to follow the margins of the free-shear zone and let the flow current take it around the obstruction. While this is an effective strategy for passing stumps and outcrops, it is, unfortunately, an ineffective strategy for passing dams

Eulerian, Lagrangian, and discrete rules (agent-based) simulation (Parrish and Edelstein-Keshet 1999). We integrate the three approaches for movement analysis using a 3-D Eulerian-Lagrangian-agent modeling, or ELAM, method (Goodwin et al. 2004a, 2004b, 2004c; Goodwin 2004), primarily derived from the integration of Goodwin et al. (2001) and Anderson (2002), although elements of it are derived from many prior efforts. The resulting ELAM construct provides the theoretical and computational basis to elicit vector-based virtual movement in response to both physicochemical stimuli from CFD and water quality models (Tischendorf 1997) or other sources of abiotic and biotic data.

In an ELAM, a 3-D Lagrangian particle-tracking algorithm is supplemented with behavioral rules (Schilt and Norris 1997) from an agent-based, event-driven foraging model (Anderson 2002) using object-oriented programming. Three-dimensional movement behavior is then implemented within a 3-D CFD model, U2RANS (Lai et al. 2003a, 2003b; Lai 2000), to take advantage of state-of-the-art numerical modeling of physicochemical fields in aquatic systems (Goodwin et al. 2001; Nestler et al. 2002, 2005). Object-orientation represents the world in a manner that corresponds to animal perceptions so that a phenomenon can be described as either an object or a field depending upon purpose of the study, scale of observation, or convention used to describe perception (Bian 2003). The notion of an "object" can often be used interchangeably with the computer term "agent." Multi-agent systems are powerful and flexible because the computer script is not centralized but distributed in a multitude of autonomous agents that can be added, eliminated, or modified without affecting the rest of the model (Ginot et al. 2002).

Physical, chemical, and biological entities that may contribute to movement behavior are defined as "agents" and make up the stimulus field that will be evaluated to determine fitness level of alternative movement directions. Potential agents include hydrodynamic, water quality, and biotic attributes. Agents identified for this application of the NFS (an ELAM), are: (a) food and predators, (b) wall-bounded flow hydraulic pattern, (c) free-shear flow hydraulic pattern, and (d) hydrostatic pressure. However, the framework is sufficiently flexible and comprehensive to allow incorporation of other agents, depending upon the needs of a study (Goodwin et al. 2004c; Anderson 2002).

Treating environmental patterns as agents is both conceptually and mathematically advantageous and corresponds to animal perceptions (Bian 2003) because encounters between fish and agents can then be defined as events (Anderson 2002). An event is defined as a change in intensity of an agent above a threshold value that triggers a response (Anderson 2002; Workman et al. 2002). Interaction between fish and an agent requires two steps: (a) an evaluation of agent attributes in the local vicinity followed by (b) a response such as a change in fish swimming speed and direction.

We model fish movement according to the SVP Hypothesis (Goodwin et al. 2004a; Goodwin 2004) described earlier. Using the SVP Hypothesis, we identify four agents that determine swim path selection: (A_0) default agent in the absence of rheotactic cues, (A_1) wall-bounded flow pattern where the change in perceived strain exceeds threshold k_1, (A_2) free-shear flow pattern where the change in perceived strain exceeds threshold k_2, (A_3) pressure (hydrostatic) where the

change in depth exceeds threshold k_3. In response to the agents, we specify the following behaviors: (B_0) swimming with the flow vector, (B_1) swimming toward increasing water velocity to minimize strain, (B_2) swimming in the direction of decreasing water velocity to minimize strain, and (B_3) swimming toward acclimated pressure (depth). Precise orientation and speed of the behaviors are fuzzed to varying levels.

A fish's perception of strain is not linear with its physical intensity. Following an analogy to sound, perceived strain, $S(t)$, is defined as the log of the sum of the absolute values of all nine Cartesian strain tensors at the fish location at time t, $I(t)$, scaled by a reference value, I_0, as:

$$S(t) = \log_{10} [\ I(t) / I_0\ ] \tag{1}$$

To characterize a perceived change in strain relative to the thresholds k_1 and k_2, we follow an analogy to the Weber-Fechner Law (Rapoport 1983), which says the "just noticeable difference" between a change in stimulus, Δs, and the background s, is $\Delta s = k \cdot s$ where k is a constant. In a similar fashion we define the perceived strain difference that elicits a behavior by the equation:

$$k_i = [\ S(t) - S_a\ ] / S_a \tag{2}$$

where k_i is the threshold level for eliciting behavior B_i, and the perceived background or acclimated strain level is S_a. Since $S(t)$ is the instantaneous perceived strain at time t, the acclimated level must represent some moving average of past and present levels. We represent the acclimated strain as an exponential moving average that can be represented as:

$$S_a(t) = (\ 1 - m_{\text{strain}}\ ) \cdot S(t) + m_{\text{strain}} \cdot S_a\ (t - 1) \tag{3}$$

where m_{strain} is an adaptation coefficient with a value between 0 and 1 that adjusts how information from the present combines with information from the past. Equation 2 implies that to elicit a behavior a larger change in strain intensity is needed at higher background levels than at lower levels and that the response depends intimately on the individual's antecedent experiences. Response to changes in hydrostatic pressure is treated using a linear difference between instantaneous and acclimated depths for k_i since depth is proportional to hydrostatic pressure as perceived by a fish's swim bladder. Acclimated depth is calculated using Equation 3 by replacing perceived strain with depth and identifying a separate adaptation coefficient m_{depth}.

To represent the changing hierarchy of responses to the agents we employ an event-based modeling structure (Anderson 2002). In each increment of time, using the cues on the presence or absence of the agents characterized by stimuli being above or below the threshold change levels, the fish tracks the expected utility of each behavior and elicits the behavior with the maximum expected utility. Based in game theory, the expected utility (U_i) from behavior B_i depends on the behavior's intrinsic utility (u_i) times the probability (P_i) of obtaining the utility, minus the bioenergetic cost (C_i) of the behavior as:

$$U_i(t) = P_i(t) \cdot u_i - C_i(t) \tag{4}$$

The probability of obtaining the utility depends on the previous probability and whether or not the fish encounters the agent in increment t - 1 to t and is expressed as an exponential moving average:

$$P_i(t) = (1 - m_i) \cdot e_i(t) + m_i \cdot P_i(t - 1) \tag{5}$$

where m_i is a memory coefficient weighting the present event and past probability $P_i(t - 1)$ and $e_i(t)$ is a Boolean measure equal to unity if the stimulus change threshold is exceeded in increment t - 1 to t and zero otherwise.

The algorithm is implemented by adding the oriented speed response (volitional swim vectors) to a Lagrangian particle-tracking algorithm dynamically linked to a 3-D Eulerian CFD model. The resulting framework of the NFS is visualized in Figure 8.

NFS Calibration

Typically, NFS calibration and evaluation involves three steps. First, using the simulated flow field for an arbitrarily selected configuration (calibration configuration), the coefficients k_i, m_{strain}, m_{depth}, m_i, and u_i are adjusted so individual virtual fish tracks calculated at 2-sec time steps resemble the predominant movement patterns of 3-D acoustic-tagged fish. However, acoustic-tag data were not available for Wanapum Dam and, therefore, we could not perform this step. We could only evaluate coefficients derived from studies at Lower Granite Dam by comparing virtual fish passage percentages with measured (radio-tagged fish) passage percentages of the 2002 MOA spill calibration configuration (Case 2002_MOA). After determining the adequacy of the test application, we then blindly applied the NFS model to the remaining four scenarios to obtain virtual fish passage percentage estimates and presented these estimates to IIHR for review and evaluation. Once we received approval from the District, we then applied the NFS model to the forecast cases.

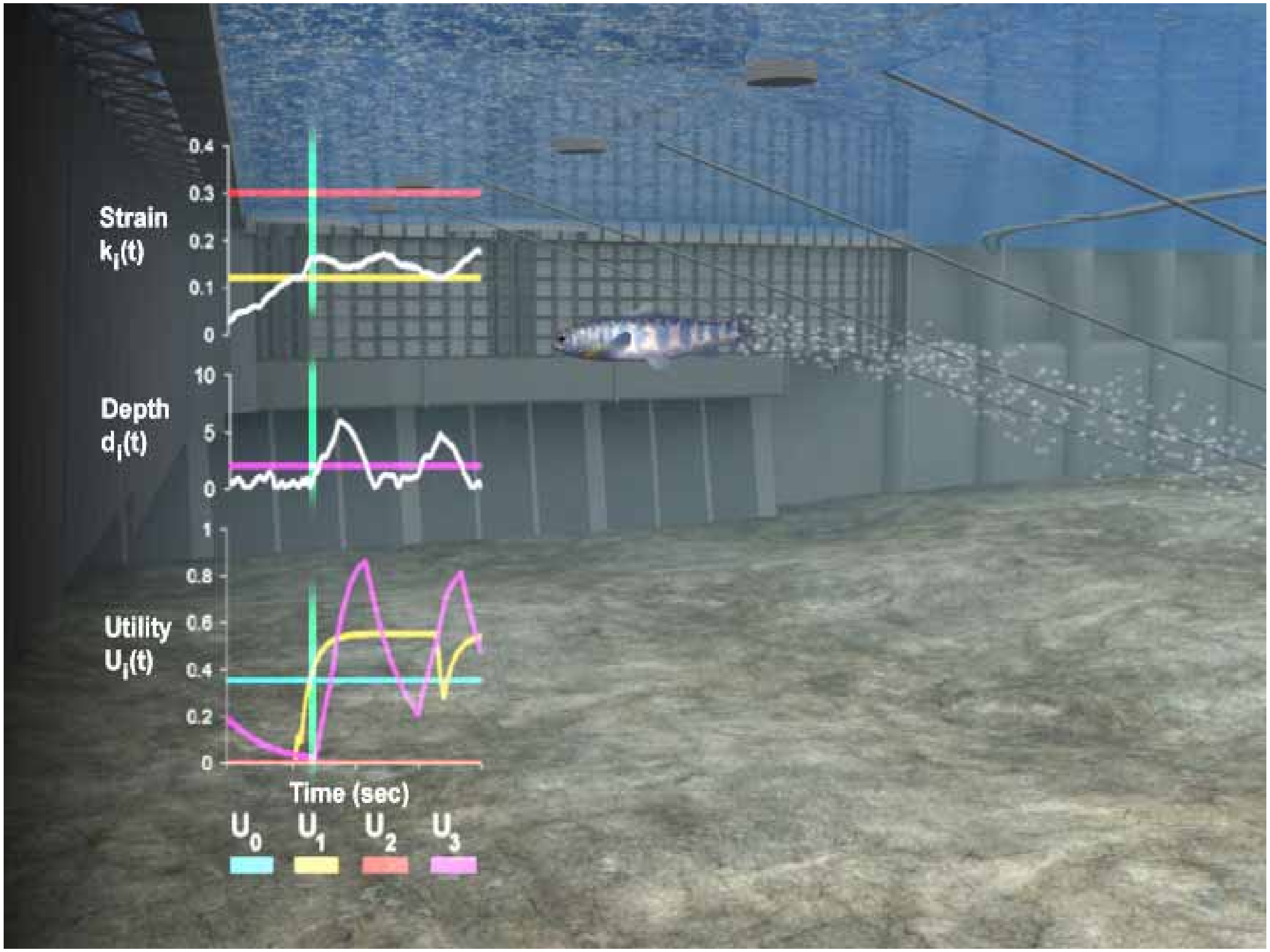

Figure 8. Visualization of the NFS model applied at Lower Granite Dam. The NFS is a Eulerian-Lagrangian-agent model (ELAM). All virtual fish orientation and speed calculations are handled by the NFS. Legend: vertical green line indicates where fish is (i.e., time t) in the NFS simulation. Legend: in Strain plot, white line is $k_i(t)$, yellow line is k_1, red line is k_2; in Depth plot, white line is $d_i(t)$, purple line is d_1; utilities and associated behaviors are as described in text.

3 Results

Phase 1

Summary comparison of virtual fish and observed passage results for all Phase 1 scenarios is provided in Table 1. Virtual fish (forecasted) passage percentages in Table 1 are based on 5,000 virtual fish and a composite vertical and 80 percent lateral virtual fish release distribution with behavior rules turned ON. Below is a more detailed breakdown of Phase 1 results. Note that the Phase 1 results discussed in detail below are based on simulations of 2,000 virtual fish. Migration of the NFS model software to U.S. Army Major Shared Resource Center (MSRC) supercomputers allowed simulation of more virtual fish. This improved capability was available only near the end of the study. Thus, early- and mid-project simulations were based on 2,000 virtual fish while final results developed at the end of this study could be based on simulations of 5,000 virtual fish.

Summary results by diel period, lateral distribution, and NFS behavior rules ON/OFF for the initial 2002 MOA spill test case (Case 2002_MOA) are presented in Figure 9. Note in all Figure 9 subplots and Figure 10 that NFS results for all three virtual fish release groupings (day, night, and composite) generally follow the same pattern with relatively little difference. Therefore, more detailed results will only be presented for the composite virtual fish release distribution. Also note that about 15 percent of the virtual fish remain (REM) in the CFD model mesh at the termination of each NFS run, making comparison more difficult. For more effective comparison, we apportioned the REM virtual fish by proportion of virtual fish using each exit route for all plots of Figure 9 except the lower-right plot. This apportioning assumes that virtual fish remaining in the CFD model mesh will use exit routes in the same proportions as previously passed virtual fish. Once this adjustment is made, then forecasted passage closely follows observed passage with maximum differences between forecasted and observed of about 2 percent. As a caution to the reader, this level of fidelity between forecasted and observed passage is unusual. Previous experience and sensitivity analysis shows that an error of about 5 to 10 percent should be expected when using the NFS because of multiple sources of error in the observed data, inconsistent and variable operation of the dam during the collection of observed passage data, and various assumptions made in the modeling process. Comparison between the upper and lower subplots of Figure 9 provides an assessment of the effect of lateral virtual fish release distribution on NFS performance. Generally, the two lateral distributions for Phase 1 show the same

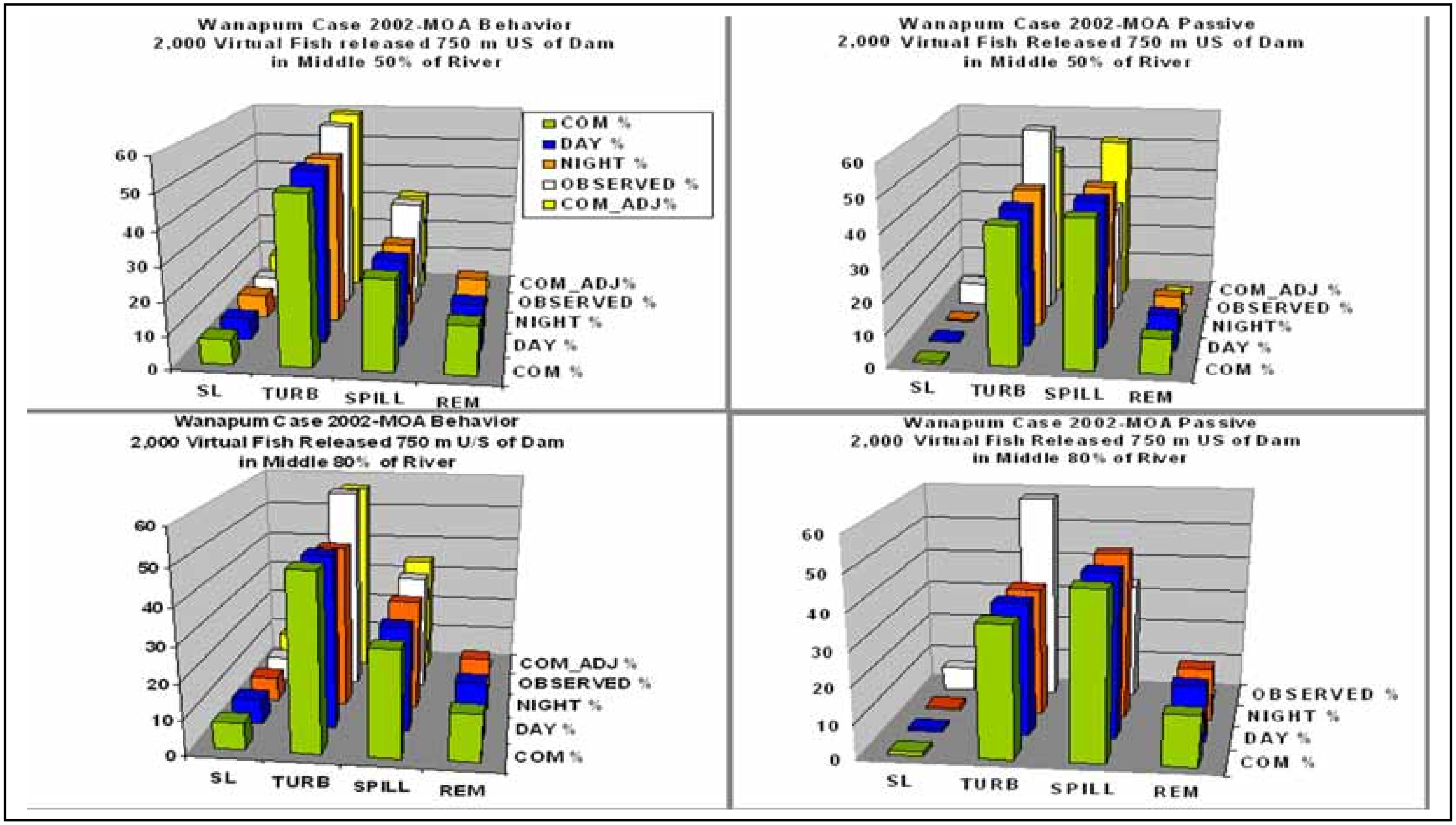

Figure 9. Phase 1 passage results for Wanapum Dam 2002 MOA spill (Case 2002_MOA) flow condition. Note the general pattern of NFS passage results closely follows observed data (LGL Limited, 2005) for all cases (DAY, NIGHT, and COMposite) in which behavioral rules were turned ON (left side plots). However, the relatively high percentage of virtual fish remaining in the CFD model mesh at the conclusion of the NFS run makes direct comparison more difficult. The back-most row (yellow) distributes the remaining migrants as explained in the text. Note the close match between forecasted and observed passage after redistribution. Note also the difference between forecasted and observed is greater when the behavior rules are turned OFF and fish movement follows passive transport (upper-right plot). Also note that passage summaries are relatively insensitive to the 50 percent versus 80 percent lateral virtual fish release distributions. Lastly, note that 2,000 virtual fish were used due to NFS computational requirements in January 2004. The existing NFS model (as of January 2005) has been significantly enhanced to allow simulation of more virtual fish. For passage results using 5,000 virtual fish see Appendix A (Legend: SL = sluice, TURB = powerhouse, SPILL = spillway, and REM = remaining)

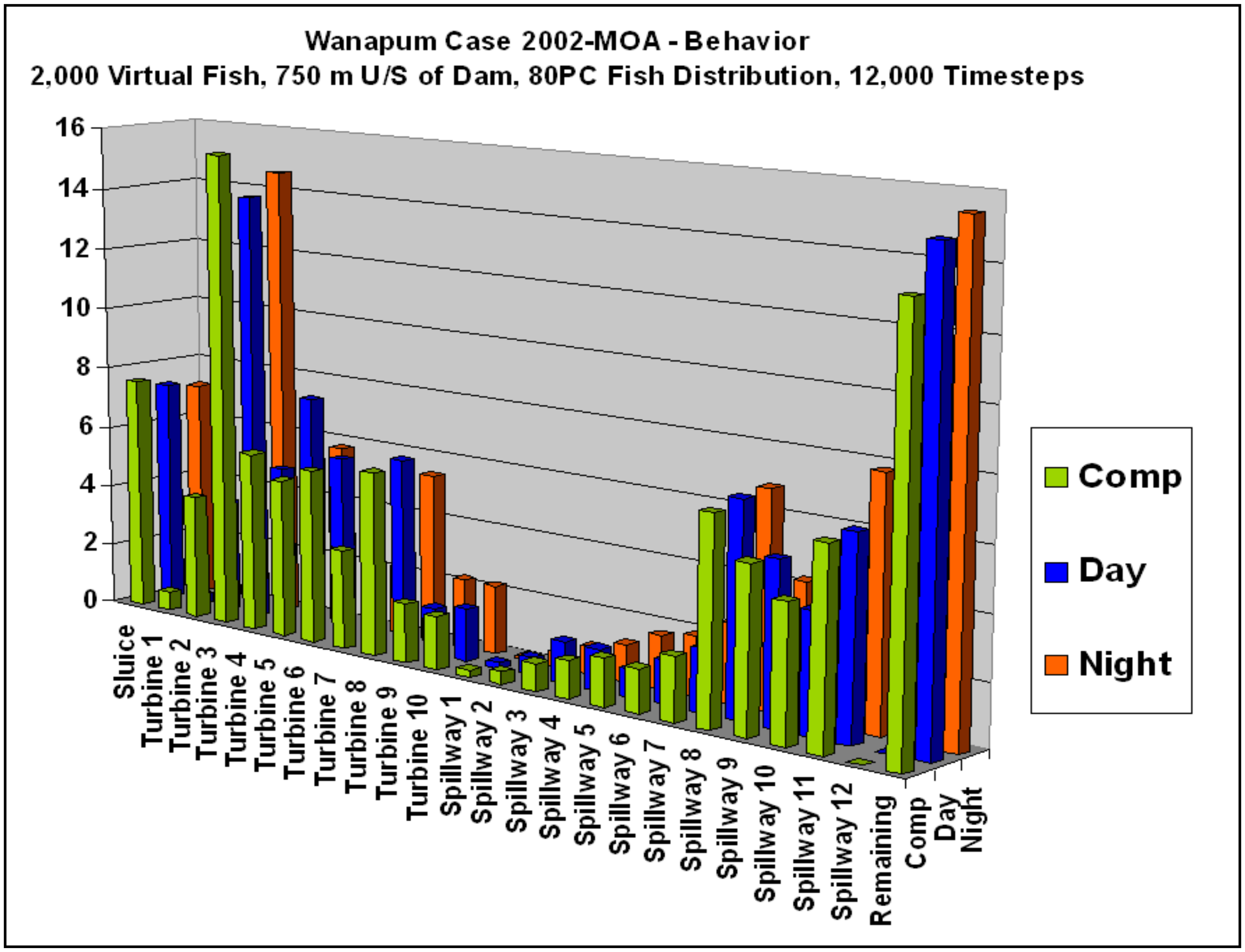

Figure 10. Detailed virtual fish passage results for Phase 1 for each outlet by vertical release distribution. Note that DAY vs NIGHT forecasts at the individual outlets exhibit more differences than when results are collapsed into powerhouse and spillway totals. Note that 2,000 virtual fish were used due to NFS computational requirements in January 2004. The existing NFS model (as of January 2005) has been significantly enhanced to allow simulation of more virtual fish. For passage results using 5,000 virtual fish, see Appendix A

results with no consistent trend as to which lateral distribution is best. Also note that the fit between forecasted and observed results for behavior-based passage are considerably better than the fit between forecasted and observed results for passive transport (behavior rules OFF) indicating that migrant behavior in the flow field must be an integral part of bypass design for this alternative. Based on the results obtained from Case 2002_MOA and consultation with IIHR, we decided not to recalibrate the NFS.

We then ran the NFS on CFD model output corresponding to the additional four test cases. The rest of the Phase 1 results reported to the District are presented in Figure 11 (Case 2001), Figure 12 (top plots are Case 2002_Mixed and bottom plots are Case 2002_TopSpill), and Figure 13 (Case 1997_AFP). Comparison results for the attraction flow prototype (Case 1997_AFP) indicate that the NFS can help detect seriously flawed bypass design alternatives.

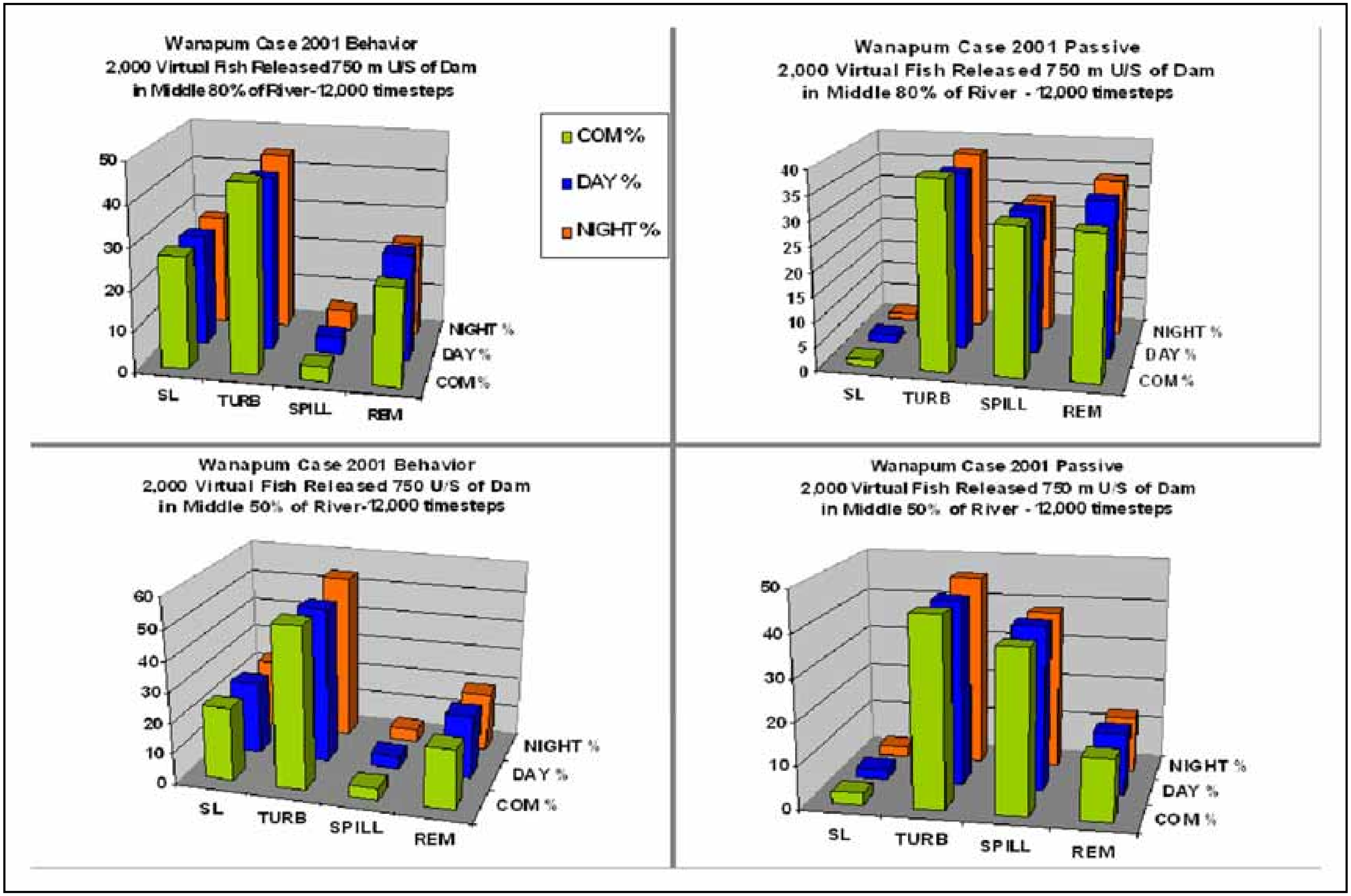

Figure 11. Phase 1 virtual fish passage results for Wanapum Dam 2001 (Case 2001) flow conditions. Note the general pattern of the NFS passage results is similar irrespective of the diel release distribution and 50 percent versus 80 percent lateral virtual fish release distributions. Note also that a comparison of passage results between behavior rules ON (left plots) and behavior rules OFF (right plots) differ significantly, implying that fish behavior is a very significant element of passage efficiency for this structural and operational scenario. Note that 2,000 virtual fish were used due to NFS computational requirements in May 2004. The existing NFS model (as of January 2005) has been significantly enhanced to allow simulation of more virtual fish. For passage results using 5,000 virtual fish see Appendix A (Legend: SL = sluice, TURB = powerhouse, SPILL = spillway, and REM = remaining)

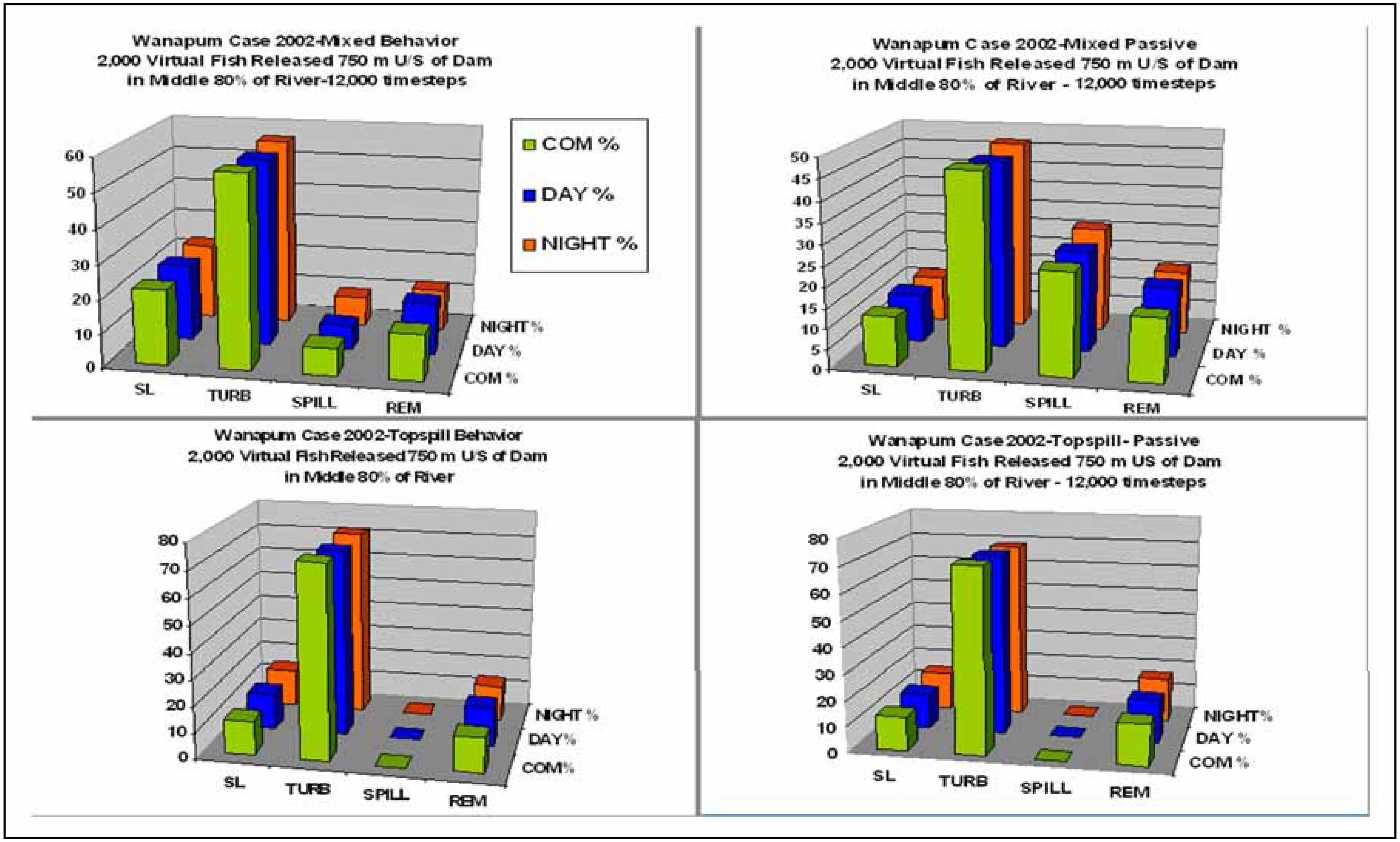

Figure 12. Phase 1 virtual fish passage results for Wanapum Dam 2002 combined spill (Case 2002_Mixed, top plots) and 2002 bulkhead top spill (Case 2002_TopSpill, bottom plots) flow conditions for the 80 percent lateral virtual fish release distributions. Results for the 50 percent lateral release distribution are not shown. Note that virtual fish (behavior rules ON) and passive transport (behavior rules OFF) are very similar for Case 2002_TopSpill, but not for Case 2002_Mixed. Note that 2,000 virtual fish were used due to NFS computational requirements in May 2004. The existing NFS model (as of January 2005) has been significantly enhanced to allow simulation of more virtual fish. For passage results using 5,000 virtual fish see Appendix A (Legend: SL = bypass, TURB = powerhouse, SPILL = spillway, and REM = remaining)

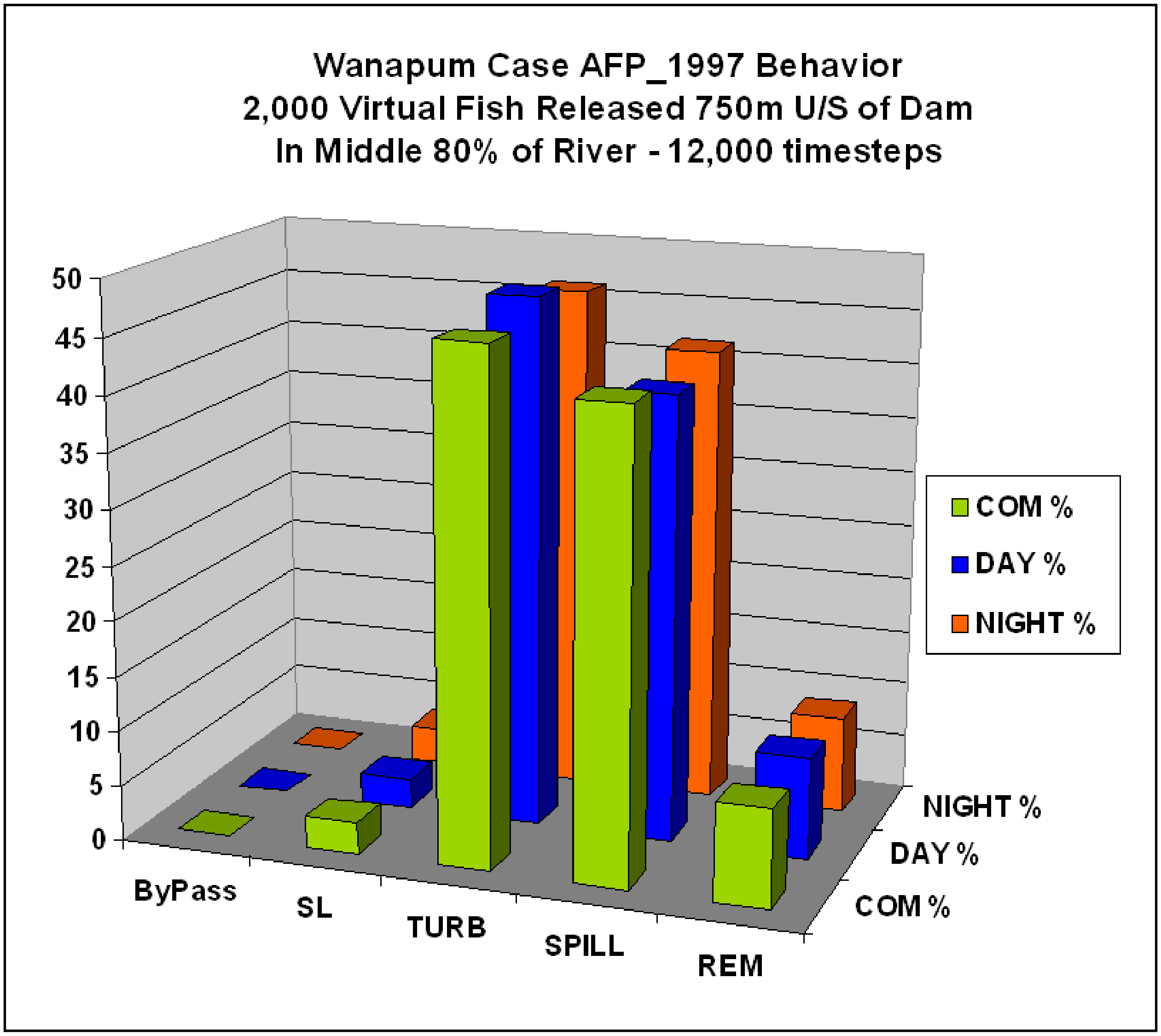

Figure 13. Phase 1 virtual fish passage results for Wanapum Dam Attraction Flow Prototype (Case 1997_AFP) flow condition and the 80 percent lateral virtual fish release distribution with behavior rules ON. Note that bypass efficiency is near 0.0. Note that 2,000 virtual fish were used due to NFS computational requirements in May 2004. The existing NFS model (as of January 2005) has been significantly enhanced to allow simulation of more virtual fish. For passage results using 5,000 virtual fish see Appendix A (Legend: SL = sluice, TURB = powerhouse, SPILL = spillway, and REM = remaining)

Phase 2

Summary results

After reviewing preliminary Phase 1 passage results (based on simulations of 2,000 virtual fish), the District requested that we apply the NFS to additional design scenarios and provided the observed radio-tagged fish passage data (LGL Limited 2005) for the other four test cases for reporting purposes. By the time the additional scenarios arrived, it was possible to run the new additional and the

original five test cases with the NFS on MSRC supercomputers, which allowed the simulation of 5,000 or more virtual fish. From concurrent NFS studies it was determined running 5,000 virtual fish provided the optimum tradeoff between runtime and stability of forecast passage results. NFS simulation results based on 5,000 virtual fish are presented for the original five test cases (Table 1) and additional scenarios (Table 2). For reference, Table 1 also lists the forecasted passage results from NFS simulations using 2,000 virtual fish and 5,000 passive particles (i.e., behavior rules turned OFF). Note the fit between observed and forecasted fish passage is generally within the expected limits of about 5 to 10 percent for the bypass systems for all five test cases. Turbine passage was overestimated relative to spillway passage for Case 1997_AFP and Case 2001 by about 20 percent. We understand from IIHR that powerhouse operation for Case 2001 was more variable than for other test cases. Flow variability is impossible to capture in a steady-state CFD model that approximates project operation using average powerhouse operation. Consequently, fidelity between flow conditions in the prototype and flow conditions as simulated in the CFD model are most different for the 2001 case. Year 1997 (Case 1997_AFP) was characterized by substantially greater river flows during the passage season than other cases. It is plausible that greater flows in 1997 resulted in migrant volitional movement rendered less effective (i.e., fish became more like passive particles in the high flows). Passive particle simulations support this plausibility. Passage results for Case 1997_AFP (Appendix A) show that virtual fish passage was more accurate when behavior rules were turned OFF (i.e., fish were advected like passive particles) than when behavior rules were turned ON. Interestingly, Case 1997_AFP is the only scenario of any existing NFS application where passage percentages based on passive transport outperformed the NFS with behavior rules turned ON.

Virtual fish bypass efficiencies for the additional scenarios ranged from 15.4 to 25.4 percent (Table 2). By themselves, forecasted virtual fish bypass efficiency differences less than 5 percent should not be used to delineate the ranking of alternatives. More detailed analyses that focus on virtual fish response to specific hydrodynamic features or detailed investigations of traces made by individual virtual fish can help refine design/operation elements and should be used to separate alternatives that are close in forecasted virtual fish bypass efficiency. Smearing of NFS results by assumptions made to create the initial lateral and vertical release distributions may smear out small or moderate design flaws or hide opportunities for improvement.

Detailed results

Detailed results for all five test scenarios and all seven additional design concepts are presented as figures in Appendix A. For each case, there is a set of five detailed figures that contains the following information:

a. Illustration of the project structural configuration obtained from the CFD model mesh provided by IIHR.

b. Color contours of velocity magnitude in m/sec (VelM) projected on the same views shown in figure type 1. Plan view and vertical cross-sectional plots also highlight the direction and relative magnitude of

VelM in the slice (i.e., the black lines/vectors). White lines on plots indicate where slice locations (depicted in other panels) are located. The same scaling is used for all contour plots of velocity magnitude for easy comparison of alternatives. The velocity magnitude is based on the CFD model results provided by IIHR.

c. Color contours of total hydraulic strain, $\sum|\partial ui/\partial uj|$, in sec^{-1} (STRXYZUVW) placed on the same views shown in figure type 1. Again, white lines on plots indicate where slice locations (depicted in other panels) are located. The same scaling is used for all contour plots of total strain for easy comparison of alternatives. The strain components are based on the CFD model results provided by IIHR.

d. Summary and outlet-specific fish passage and project flow configuration information with behavior rules turned ON. Upper-left plot provides summary project fish passage. Upper-right plot provides the summary project flow configuration. Middle-horizontal plot provides outlet-specific project fish passage. The bottom plot provides the outlet-specific project flow configuration.

e. Summary and outlet-specific fish passage and project flow configuration information with behavior rules turned OFF (passive transport). The organization of this plot is the same as for figure type 4.

The following notation is used in most figures.

WAN	=	Wanapum Dam
Rel	=	release
5k	=	5,000 virtual fish
Passive	=	passive transport (behavior rules turned OFF)

4 Discussion

Applicability

The general results from Phase 1 forecasts and the more detailed forecasts from Phase 2 indicate that the NFS is a viable technology for use at Wanapum Dam to assess different bypass design alternatives. Interestingly, the results appear useful even though hatchery yearling Chinook dominates passage composition at Wanapum Dam whereas Lower Granite Dam (where NFS model coefficients were derived) is dominated by hatchery steelhead. Also, the ability of the NFS to match the low bypass performance observed of the attraction flow prototype (AFP) (Case 1997_AFP) provides additional confidence that flawed alternatives can be identified by the NFS.

The NFS is an ELAM driven by a mechanistic “plug-and-play” behavior algorithm that embodies a biological hypothesis of how migrants synthesize hydrodynamic pattern to select swim paths. NFS performance is limited by the robustness of the biological hypothesis and accuracy and resolution of the CFD model. The ability of this NFS application to match observed data relatively closely suggests that the SVP Hypothesis as described in the conceptual model is a good approximation of the strategy used by migrants to hydraulically navigate through complex flow fields. It also suggests that the ELAM framework used to implement the SVP Hypothesis is adequate for the purposes of this study. However, like all forecasting tools, we anticipate that the NFS will improve with further use.

Sources of Model Error

Identifying and controlling model error is a critical element for any forecasting tool. Several factors contribute to model error. First, virtual fish are presently simulated as being of a uniform size and species composition. Hydrodynamic sources, however, can be detected farther away by larger fish (Coombs 1999). Second, factors such as starvation, physiological activities, prior history, age, and infections are known to influence physicochemical preferenda (Birtwell et al. 2003); these factors are not presently accounted for in the NFS. Third, bypass efficiencies may have a probabilistic component determined, in part, by whether a fish is wild or hatchery-reared (Haro et al. 1998). Fourth, we used a RANS CFD model to simulate the steady-state hydrodynamic field, whereas the field is really dynamic. Fifth, we did not have detailed (turbine- or spillbay-specific) fish passage data for fine-scale calibration nor did we have acoustic-tag

data available to determine if yearling hatchery Chinook behave differently than yearling hatchery steelhead. Sixth, the descriptions of the hydrodynamics in the Wanapum Dam forebay are based on RANS modeling that smears out turbulent structure and is limited in describing the spatiotemporal characteristics of small-scale hydrodynamic phenomena. Seventh, the movement of virtual fish do not account for fish fatigue or more biologically complex swimming behavior. These factors may be of importance to understanding why the NFS with behavior rules turned ON underperformed the NFS with rules turned OFF (passive behavior) in the high flow condition of 1997.

Conclusions and Recommendations

Results of Wanapum Dam NFS analysis indicate the NFS can be used to reduce uncertainty and, therefore, the cost and impact on salmon in the process of designing and operating bypasses. Telemetry and passage data available to calibrate the NFS for Wanapum Dam could be improved. We have two major recommendations if the District decides to use the NFS to help guide their design decisions. First, turbine- and spillbay-specific passage data should be provided for detailed calibration. Second, individual fish trace information should be made available so that we can determine the response of migrants to specific hydrodynamic features. We are concerned that the available calibration data are insufficient to uncover substantial differences in movement behavior, if they exist, between steelhead and Chinook.

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Appendix A
Detailed Results

Detailed results for all five test scenarios and all seven additional design concepts are presented in Figures A1-A12. For each case, there is a set of five detailed figures that contains the following information.

a. Illustration of the project structural configuration obtained from the CFD model mesh provided by IIHR.

b. Color contours of velocity magnitude in m/sec (VelM) projected on the same views shown in figure type 1. Plan view and vertical cross-sectional plots also highlight the direction and relative magnitude of VelM in the slice (i.e., the black lines/vectors). White lines on plots indicate where slice locations (depicted in other panels) are located. The same scaling is used for all contour plots of velocity magnitude for easy comparison of alternatives. The velocity magnitude is based on the CFD model results provided by IIHR.

c. Color contours of total hydraulic strain, $\sum|\partial ui/\partial uj|$, in sec^{-1} (STRXYZUVW) placed on the same views shown in figure type 1. Again, white lines on plots indicate where slice locations (depicted in other panels) are located. The same scaling is used for all contour plots of total strain for easy comparison of alternatives. The strain components are based on the CFD model results provided by IIHR.

d. Summary and outlet-specific fish passage and project flow configuration information with behavior rules turned ON. Upper-left plot provides summary project fish passage. Upper-right plot provides the summary project flow configuration. Middle-horizontal plot provides outlet-specific project fish passage. The bottom plot provides the outlet-specific project flow configuration.

e. Summary and outlet-specific fish passage and project flow configuration information with behavior rules turned OFF (passive transport). The organization of this plot is the same as for figure type 4.

The following notation is used in most figures.

WAN= Wanapum Dam

Rel = release

5k = 5,000 virtual fish

Passive = passive transport (behavior rules turned off)

Figures A1-A12 present the five test scenarios and the seven additional design concepts as follows:

Figure A1. Wanapum Dam, Case 1997_AFP

Figure A2. Wanapum Dam, Case 2001

Figure A3. Wanapum Dam, Case 2002_Mixed

Figure A4. Wanapum Dam, Case 2002_MOA

Figure A5. Wanapum Dam, Case 2002_TopSpill

Figure A6. Wanapum Dam, Case Cncpt10_20K

Figure A7. Wanapum Dam, Case Cncpt10_10K

Figure A8. Wanapum Dam, Case Cncpt10_5K

Figure A9. Wanapum Dam, Case Cncpt11_20K

Figure A10. Wanapum Dam, Case Cncpt11_10K

Figure A11. Wanapum Dam, Case Cncpt11_5K

Figure A12. Wanapum Dam, Case TSB_AFP

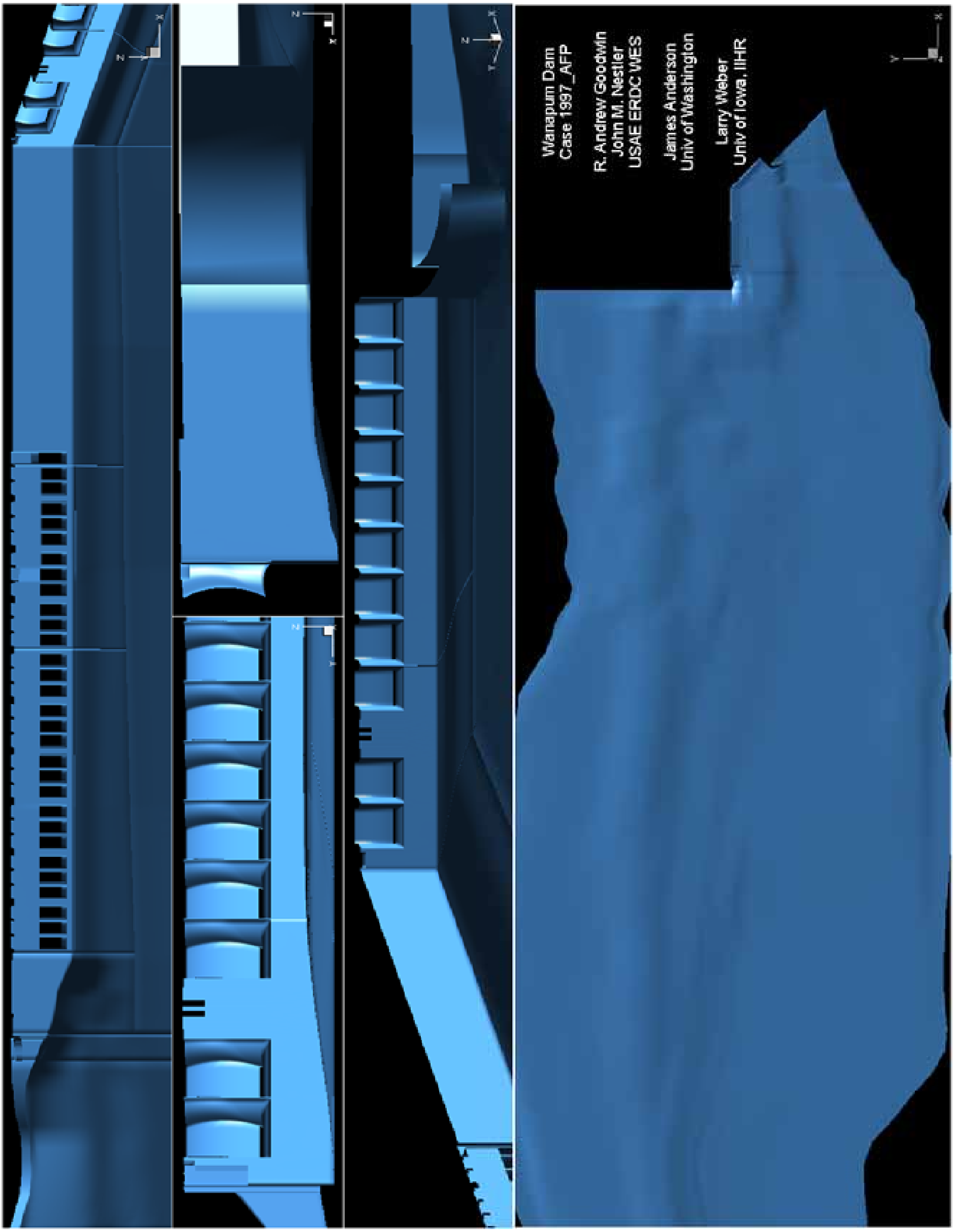
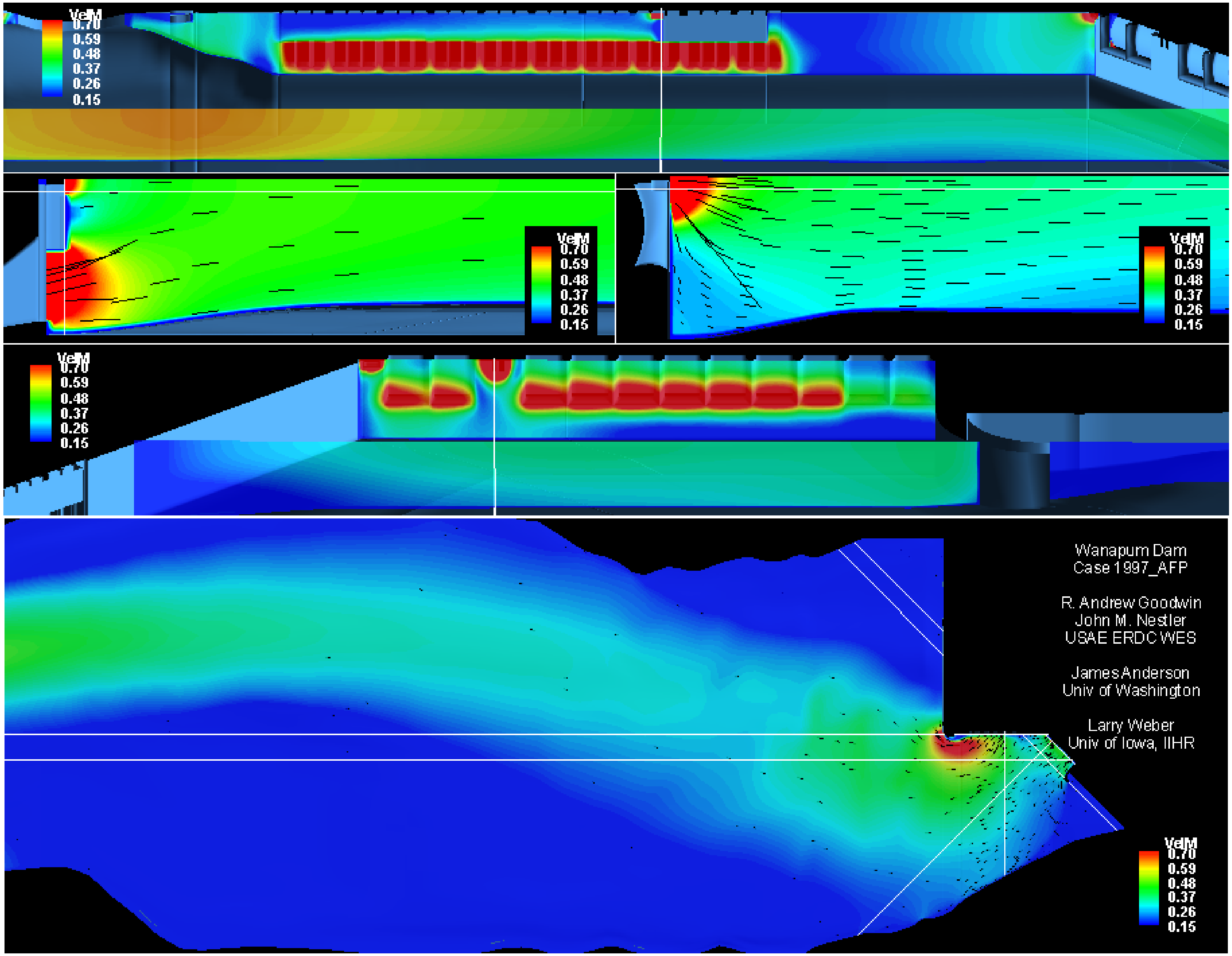


Figure A1. Wanapun Dam, Case 1997_AFP (Sheet 1 of 5)



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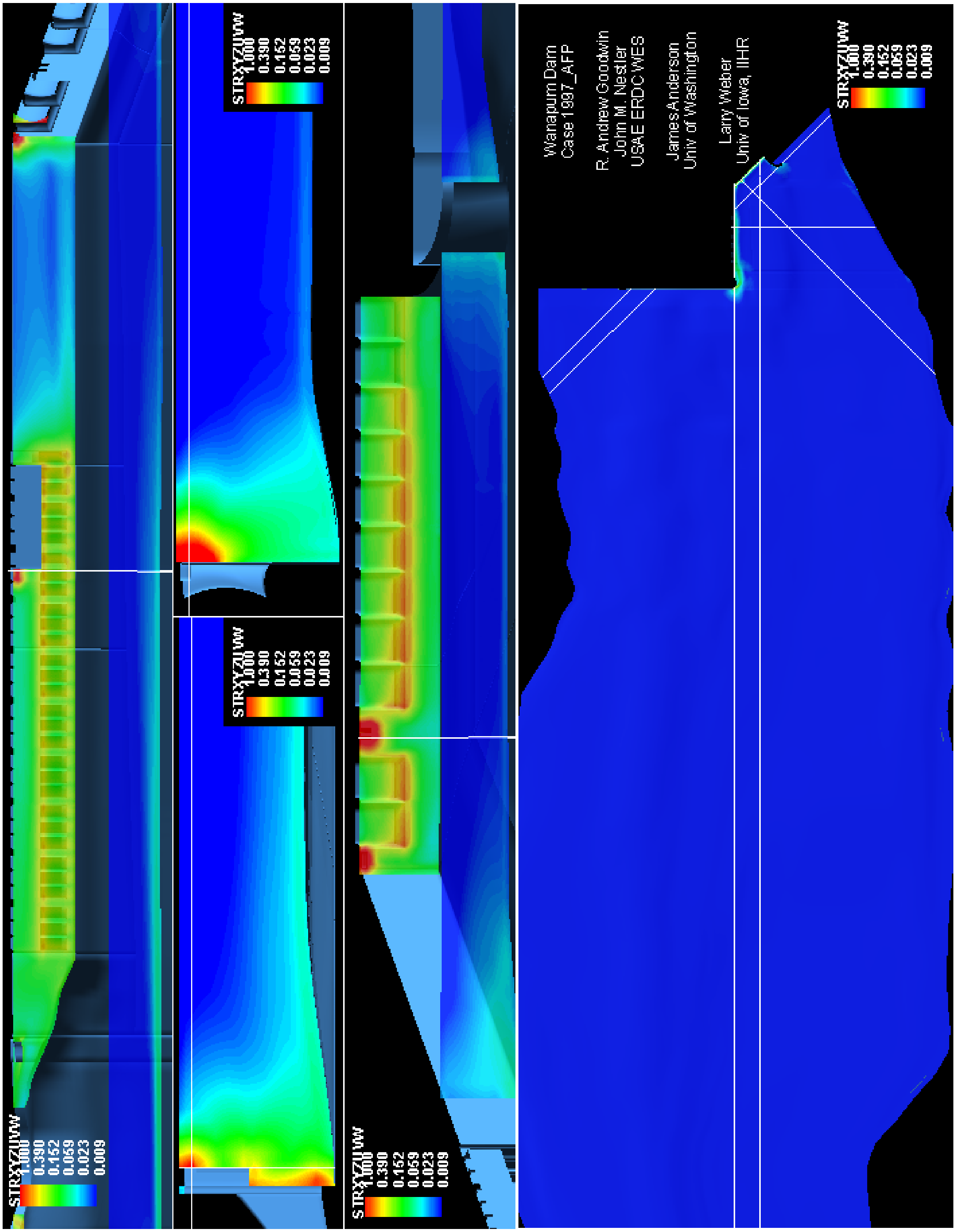

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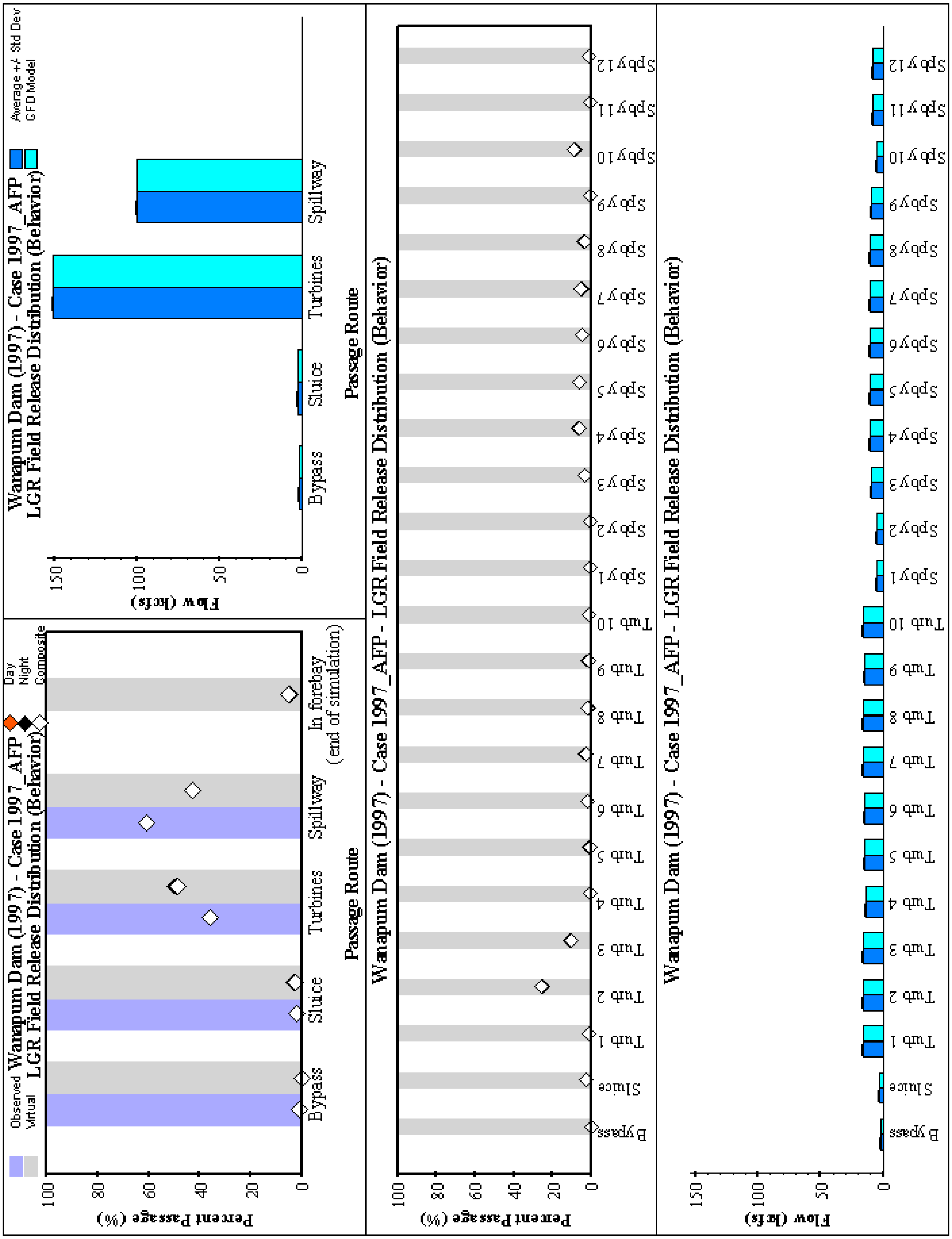

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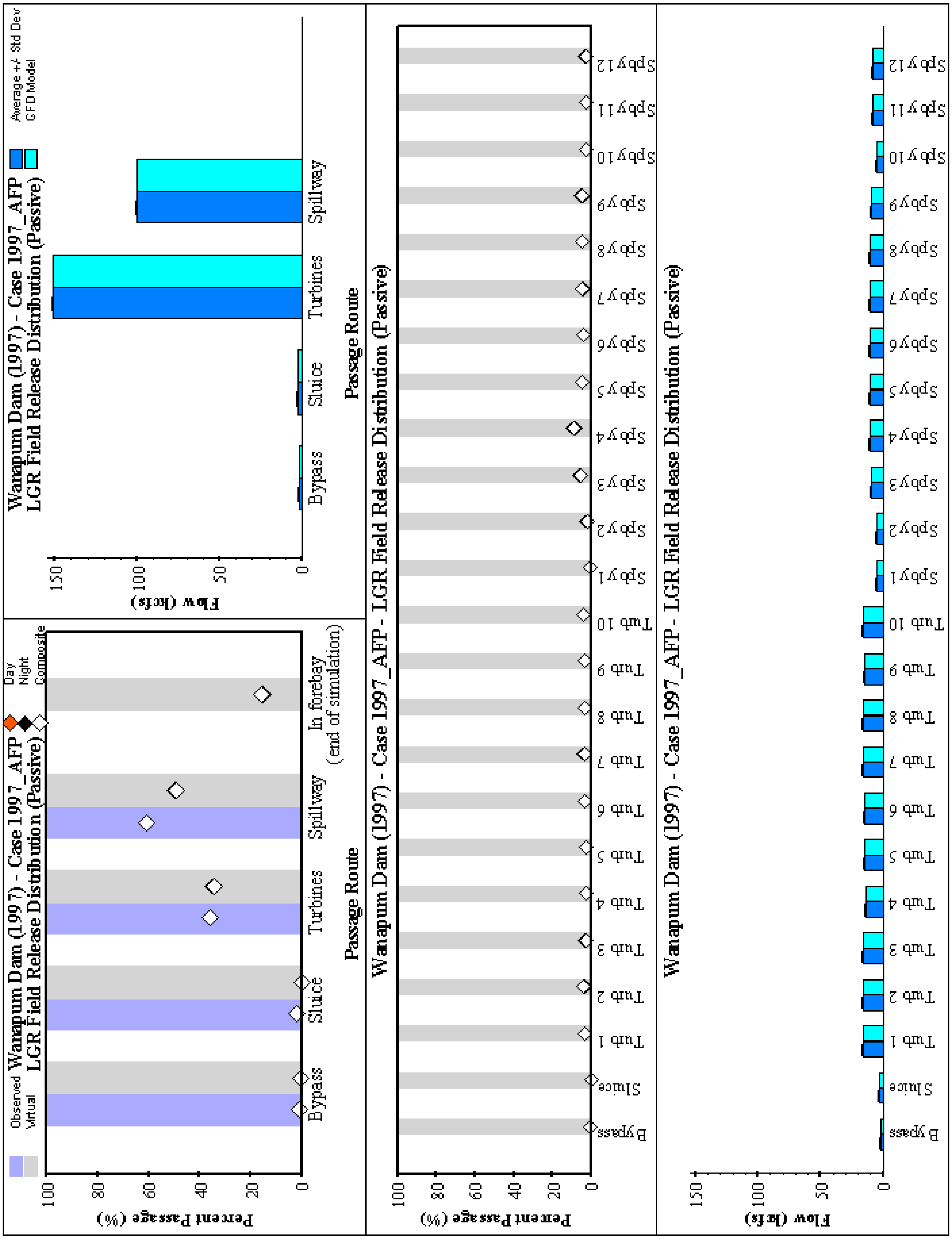

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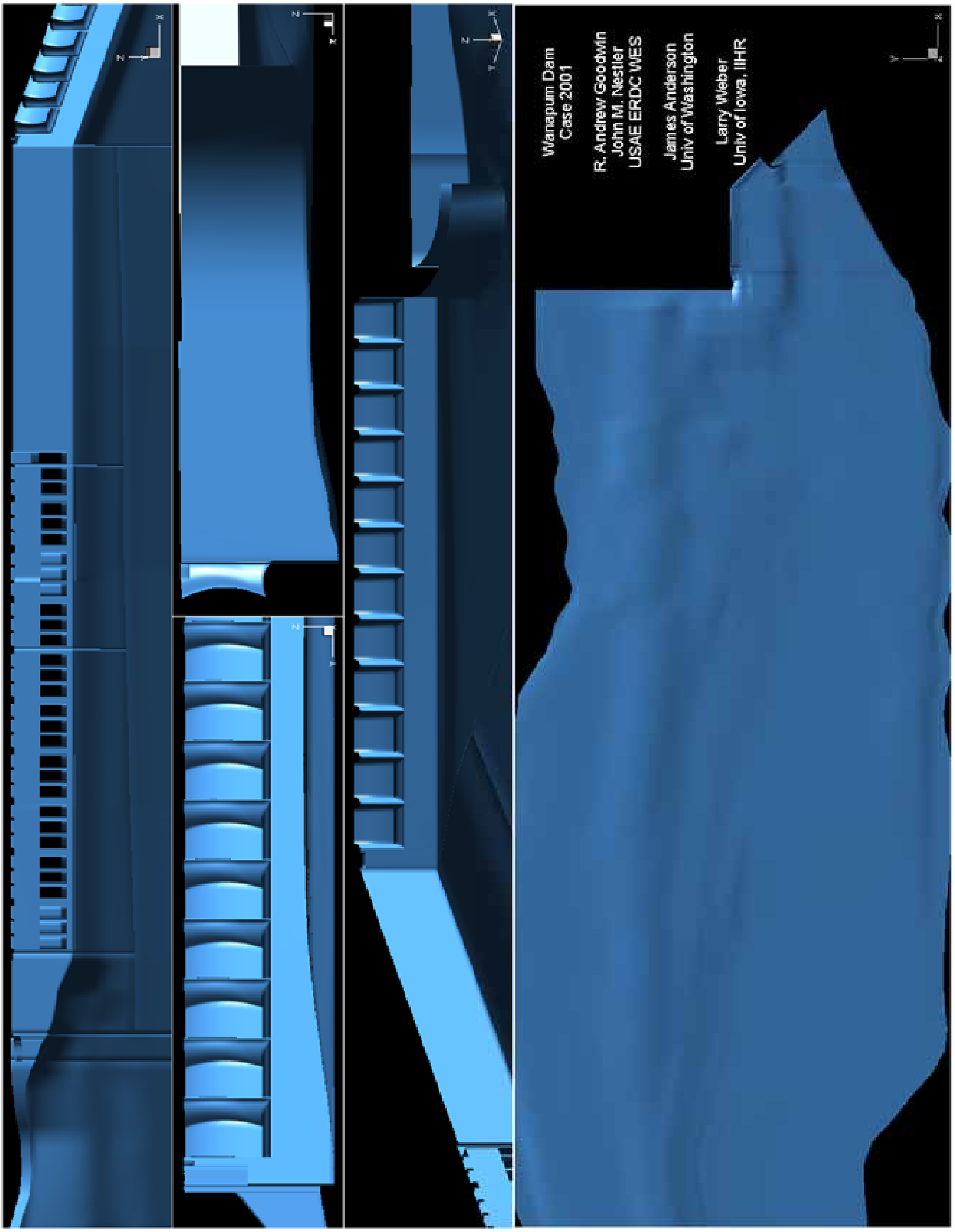
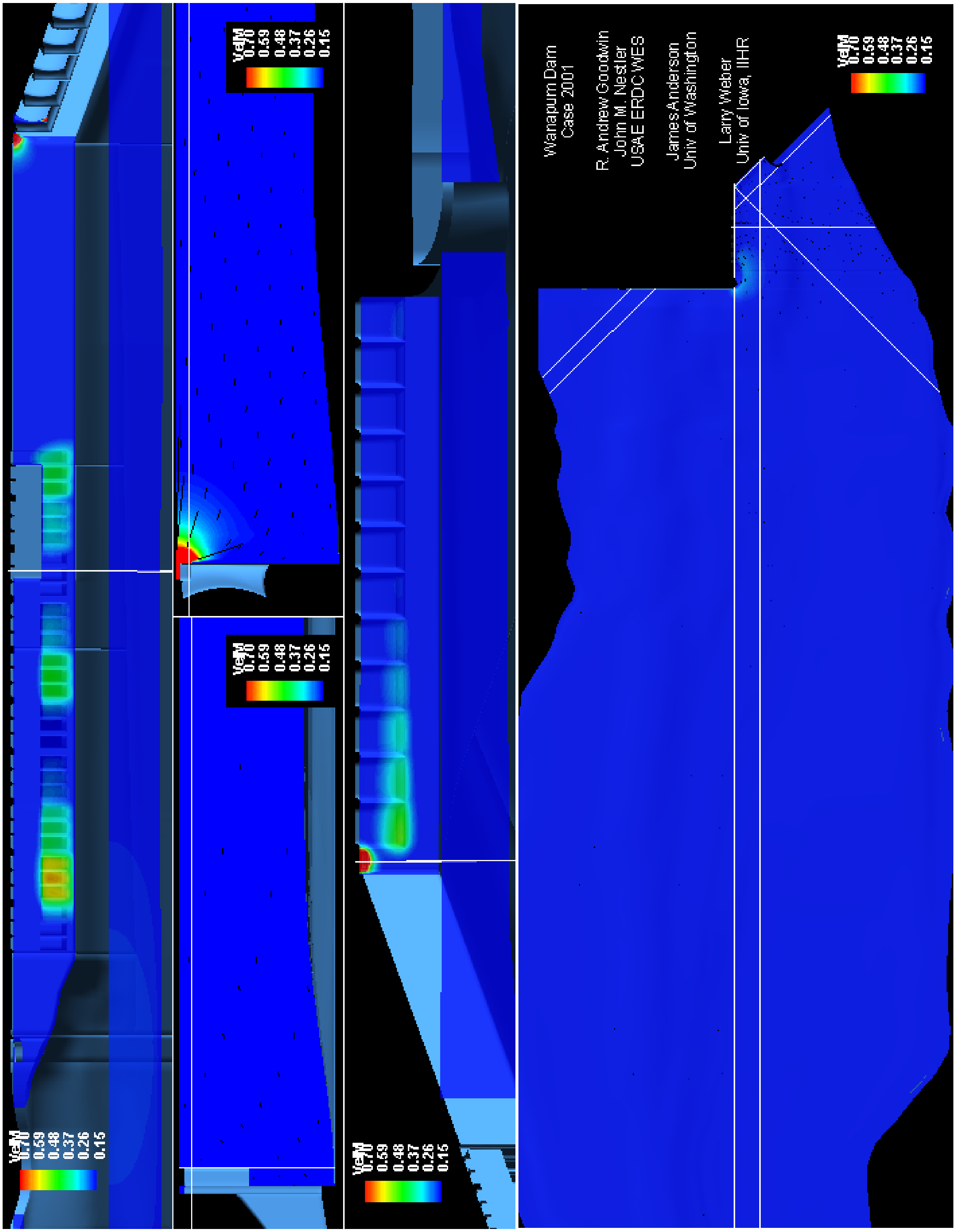


Figure A2. Wanapum Dam, Case 2001 (Sheet 1 of 5)



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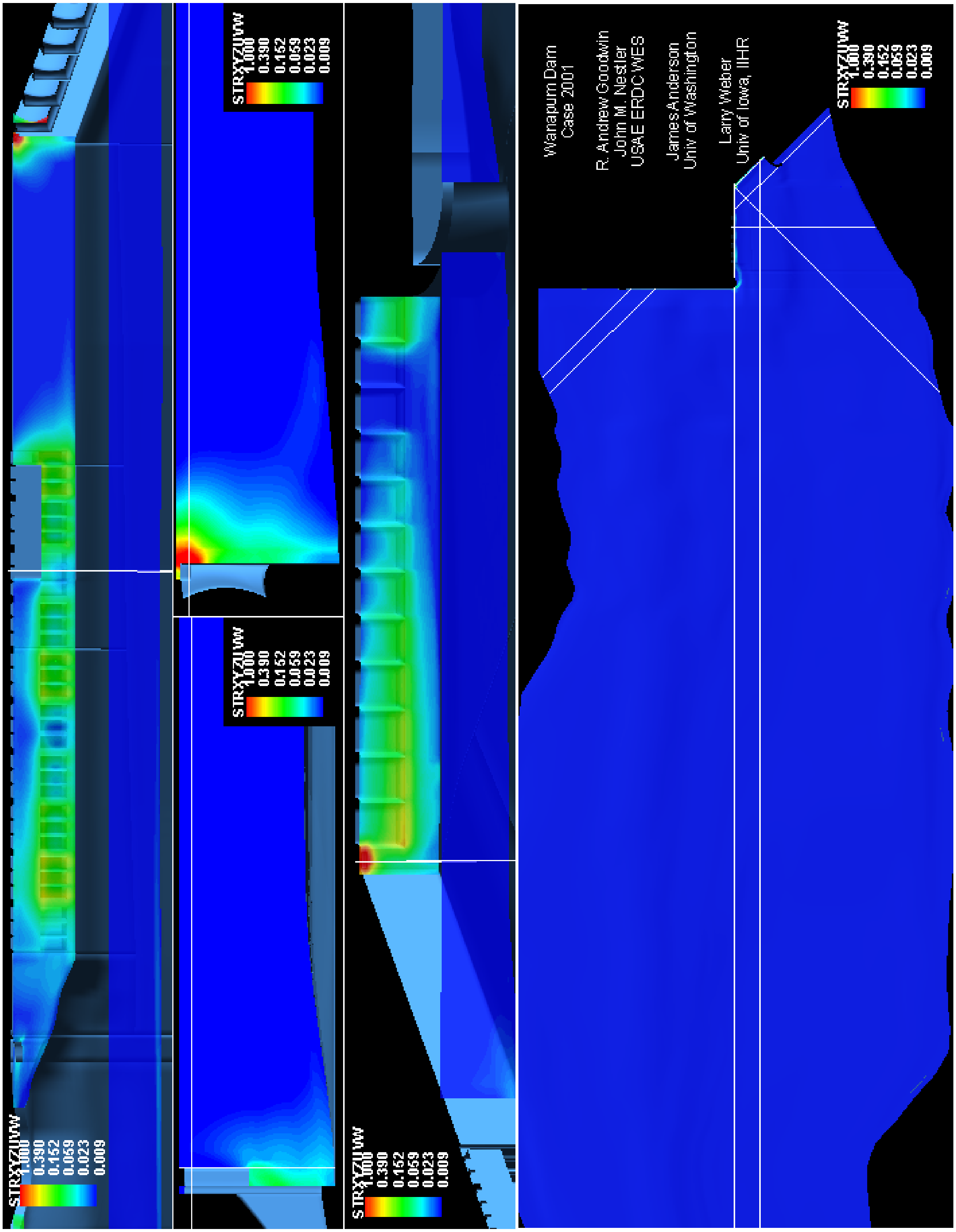

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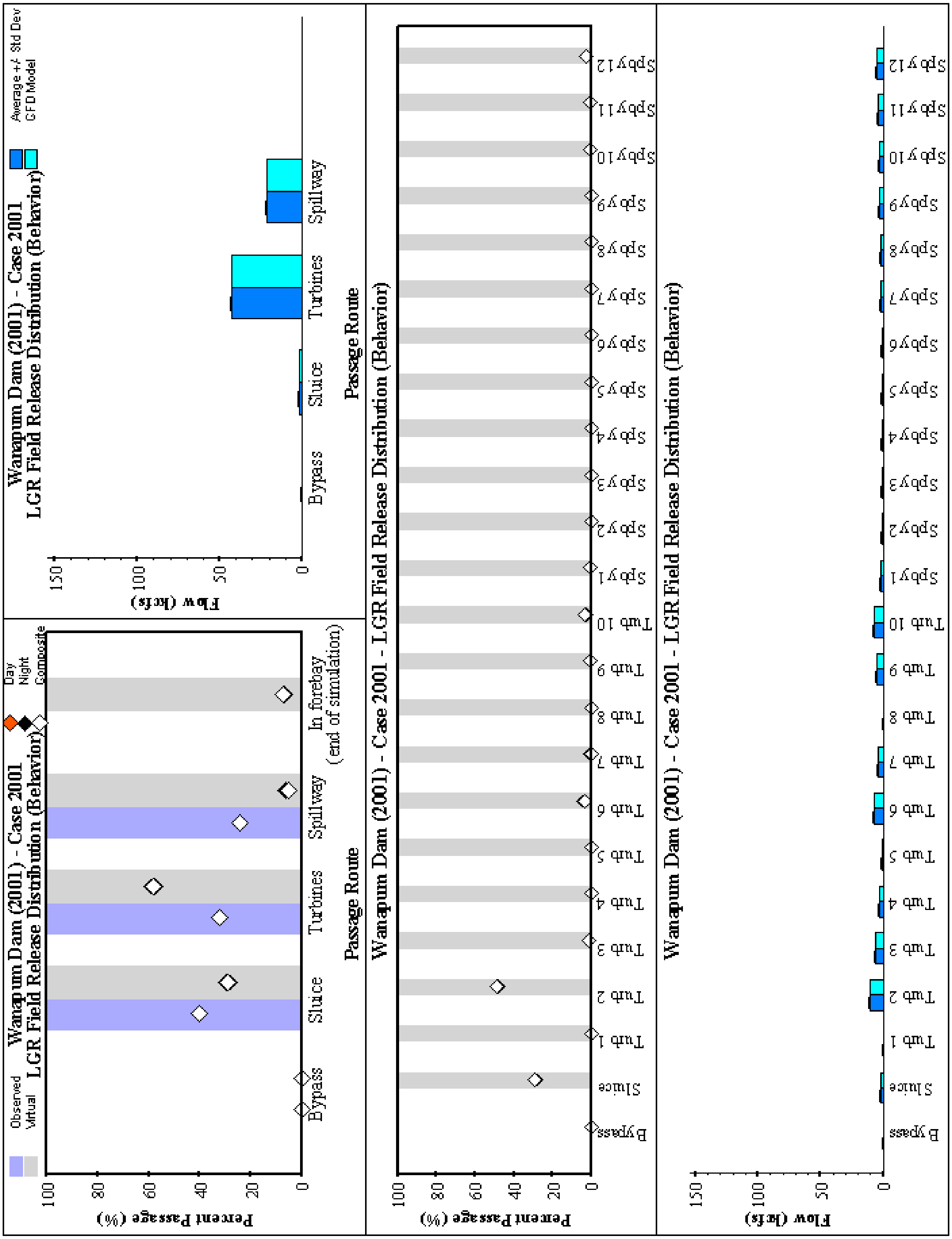

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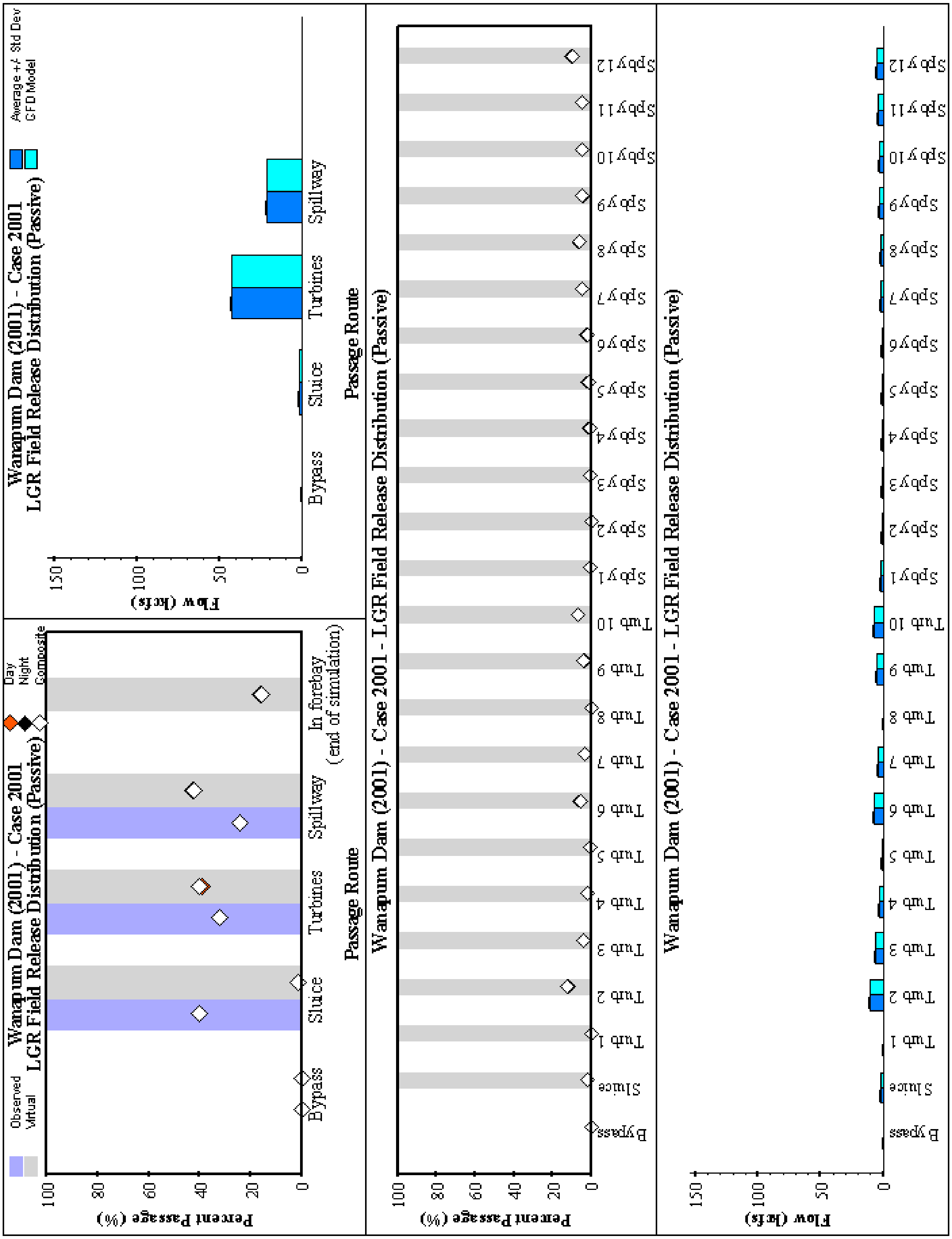

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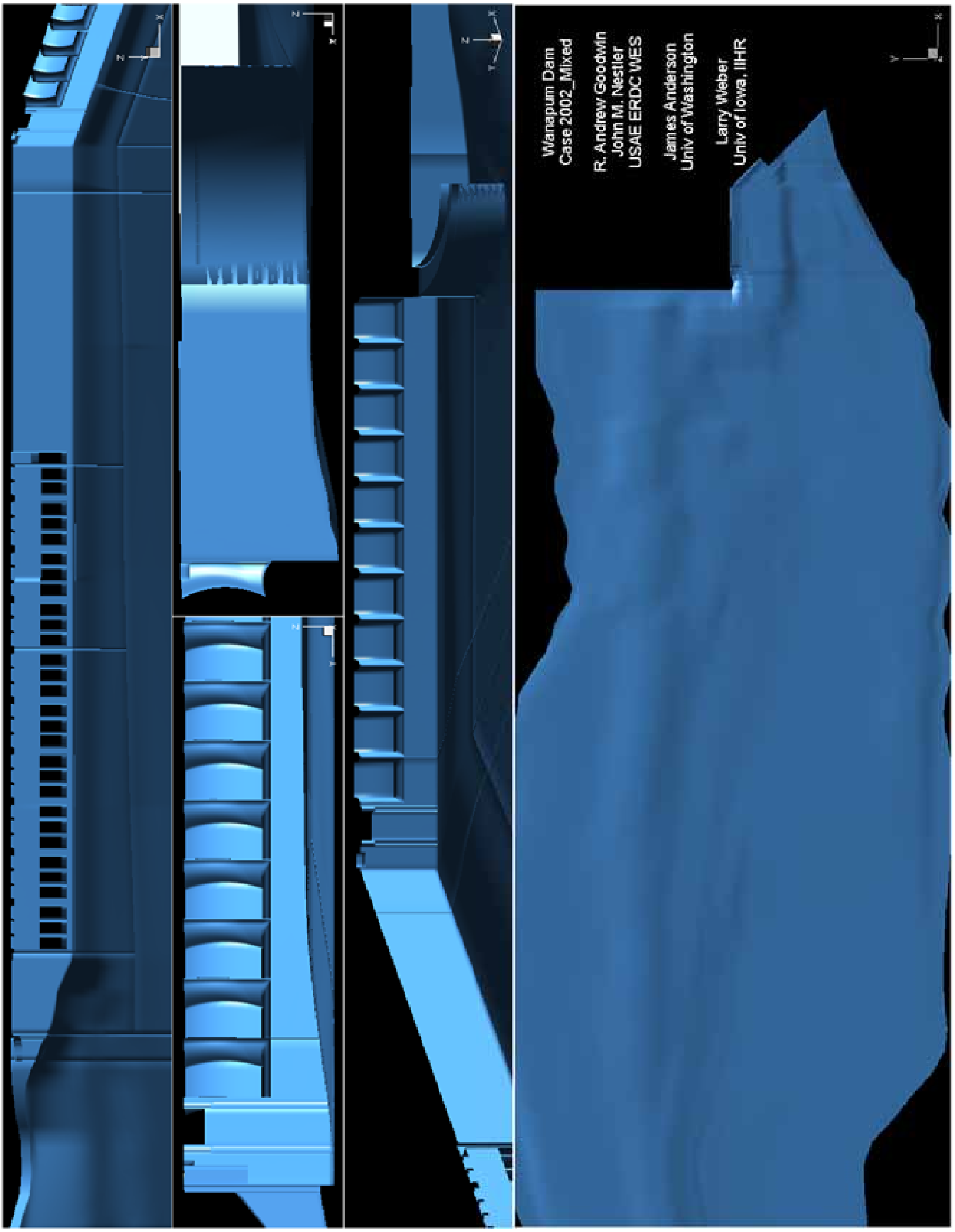
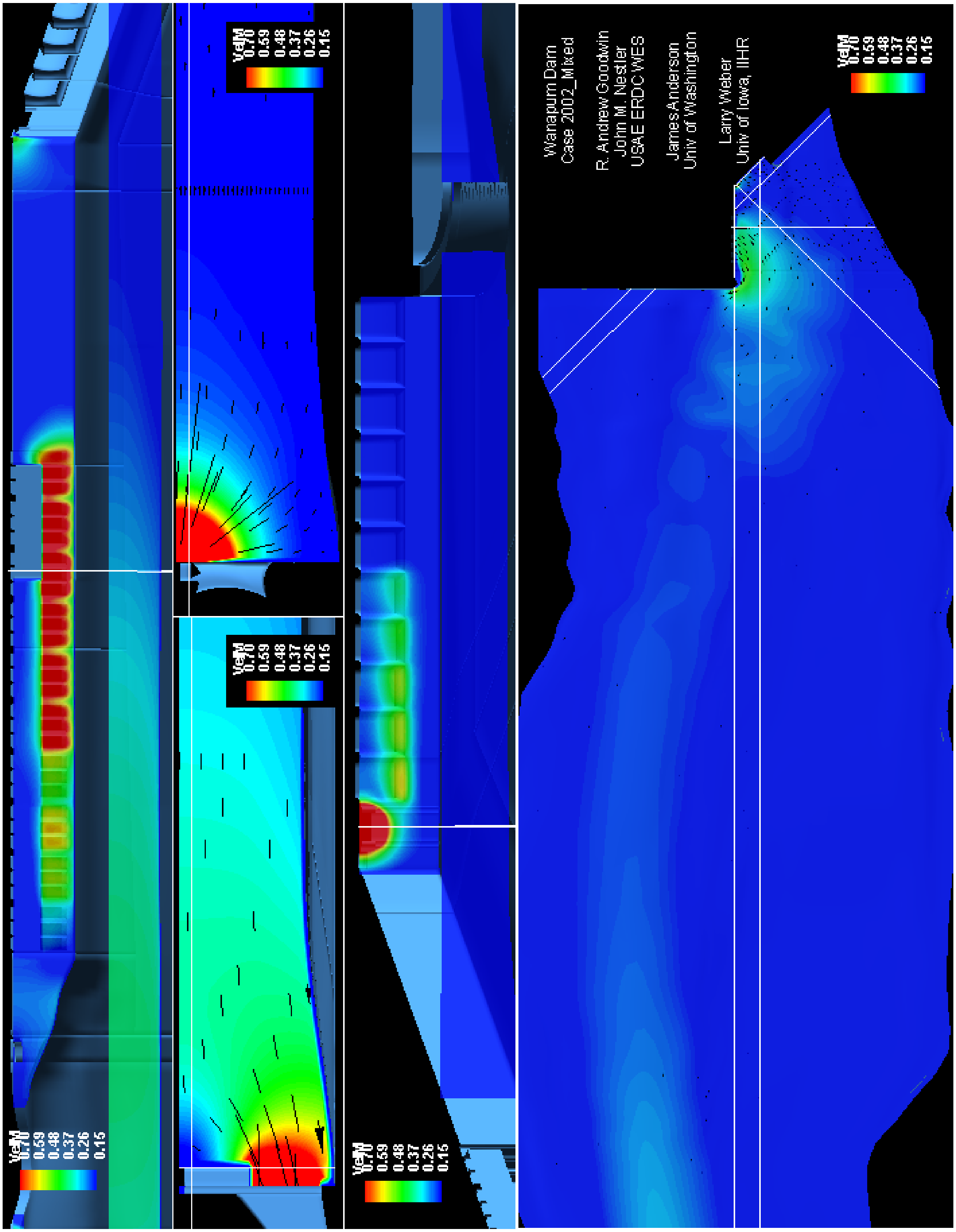


Figure A3. Wanapum Dam, Case 2002_Mixed (Sheet 1 of 5)



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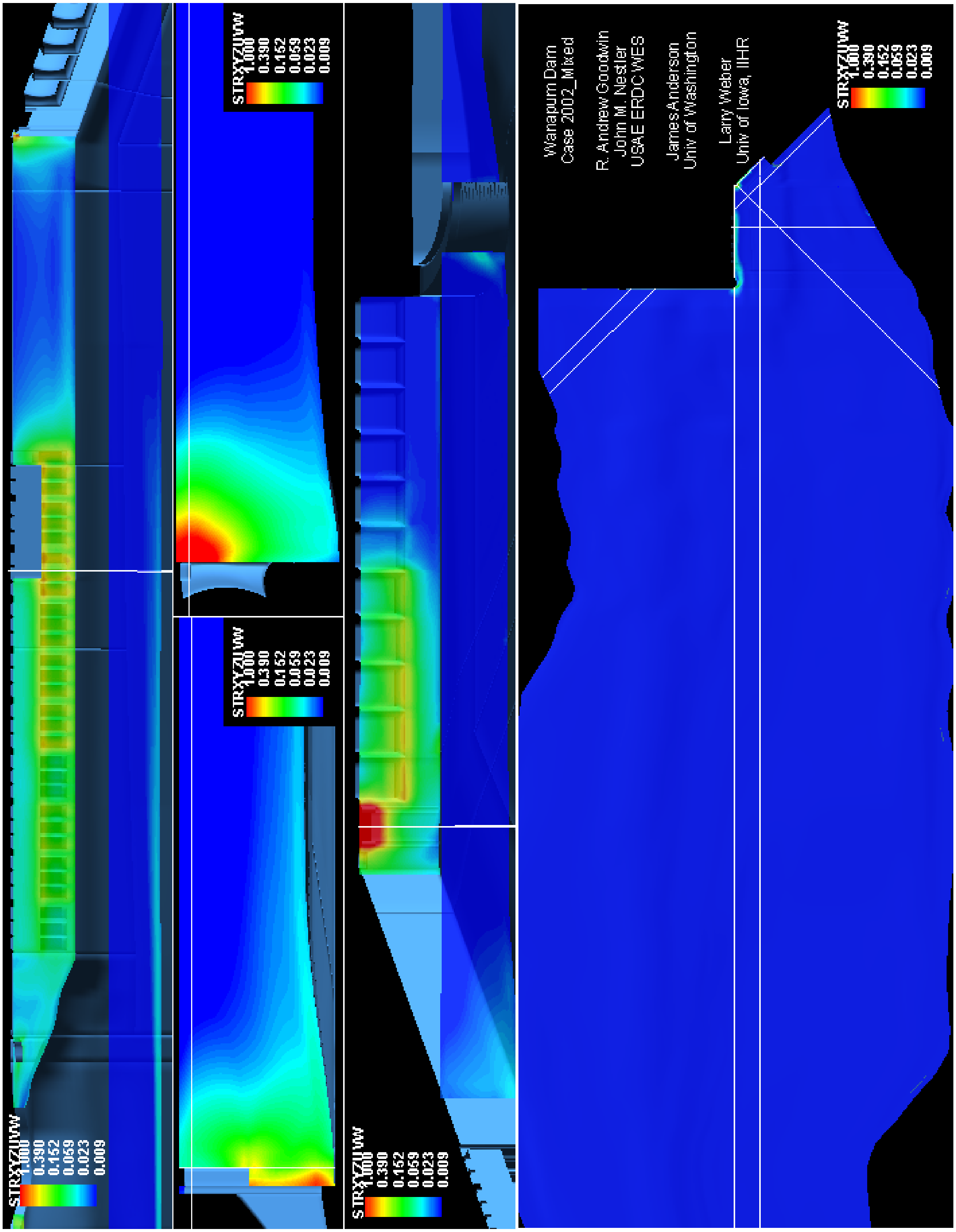

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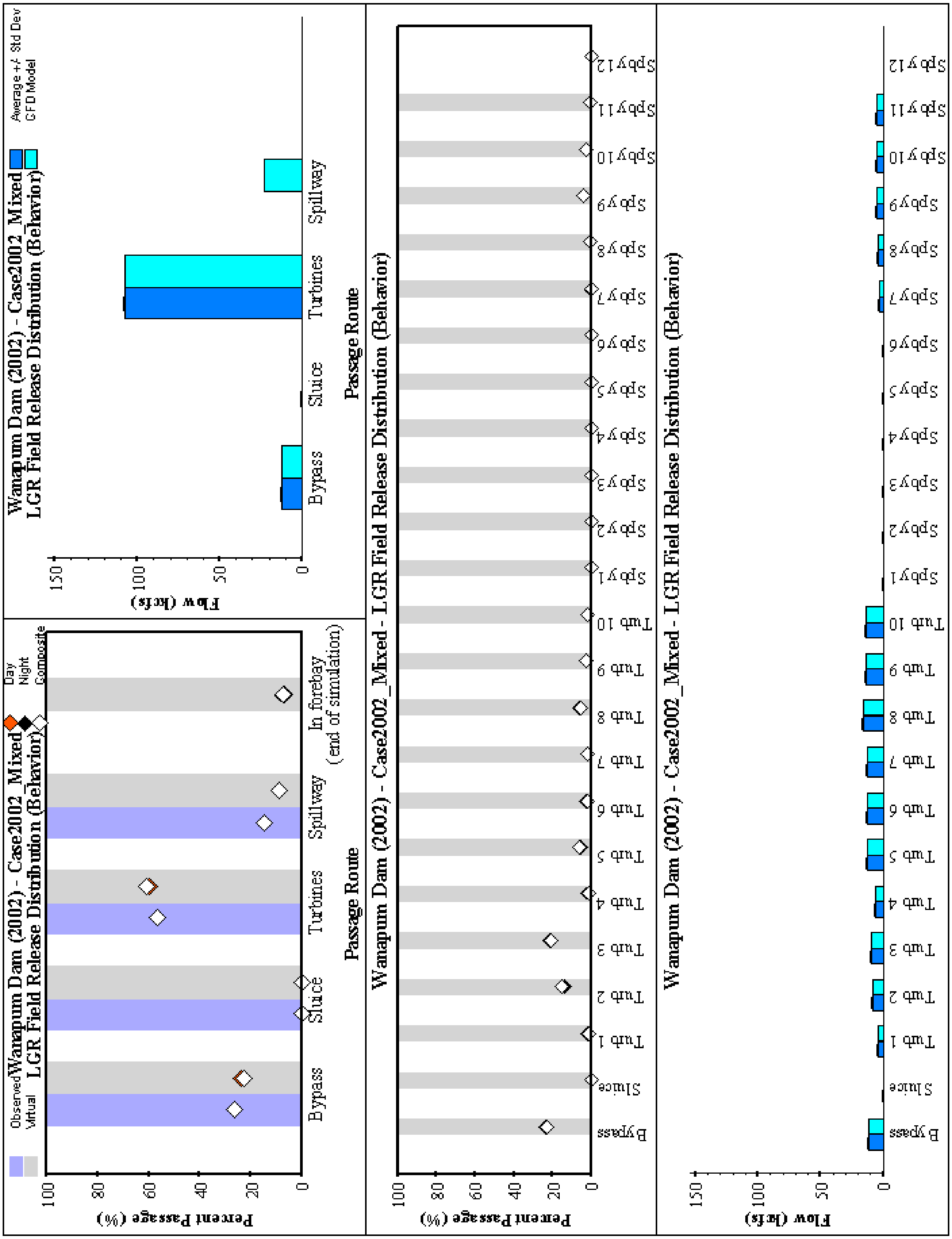

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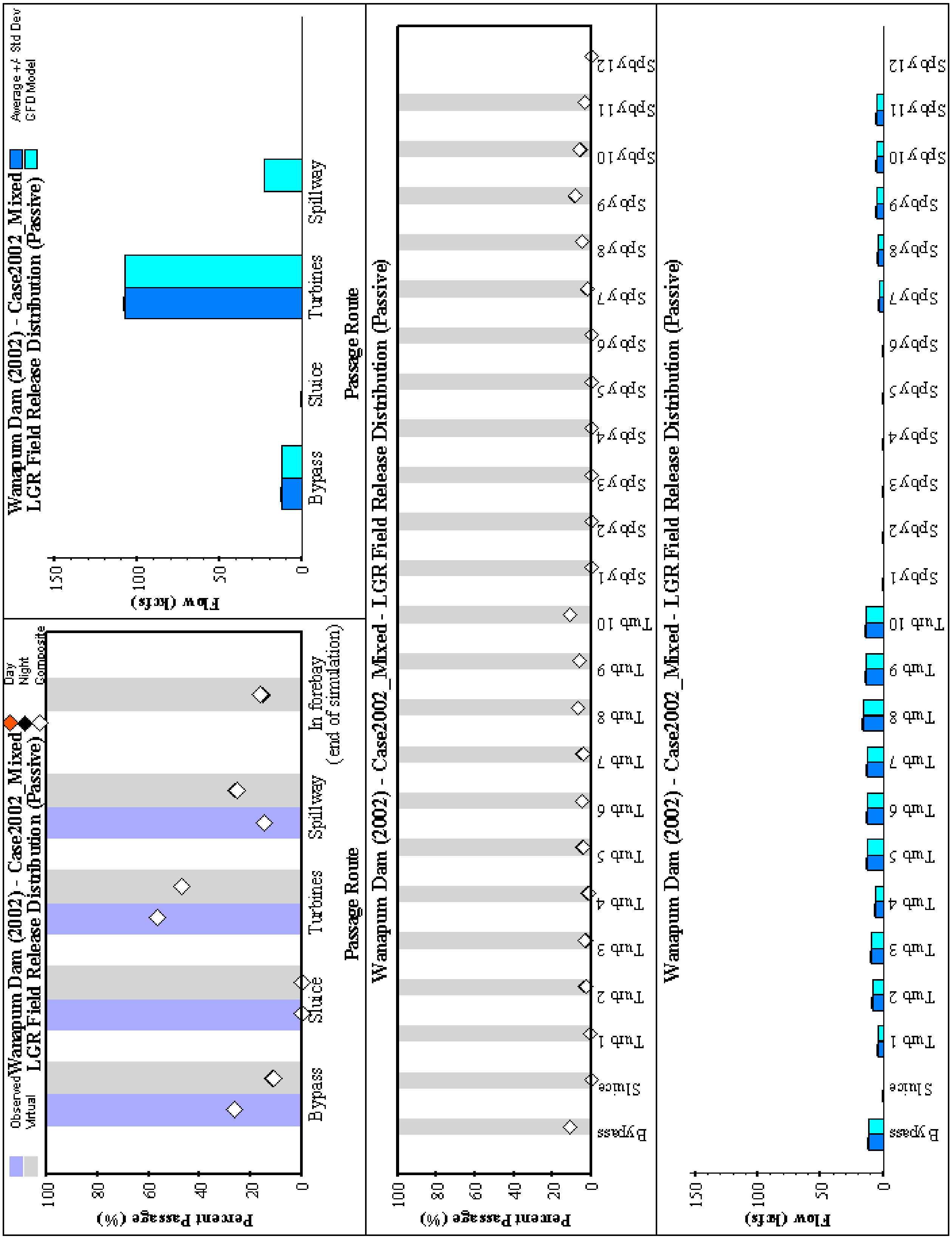

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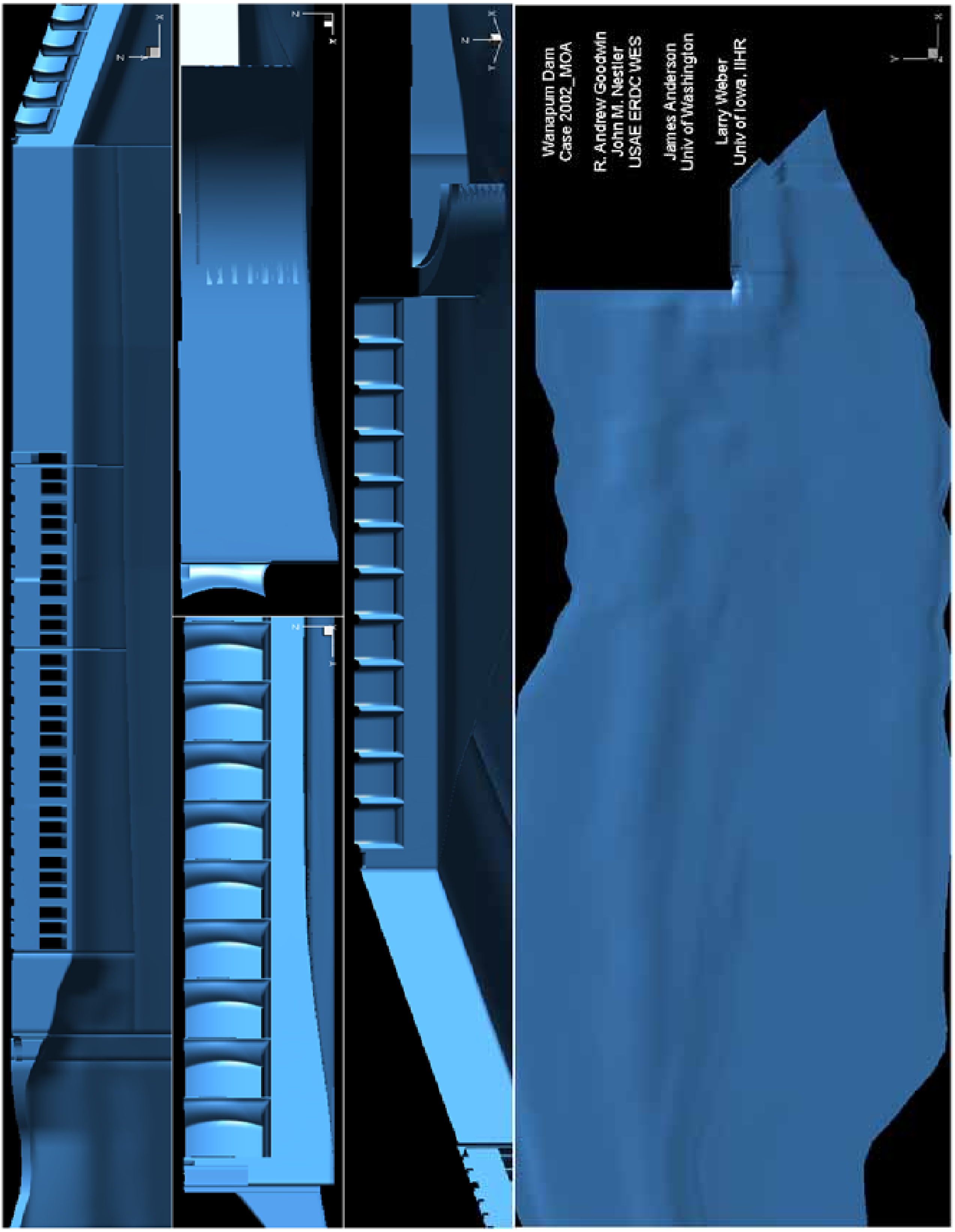

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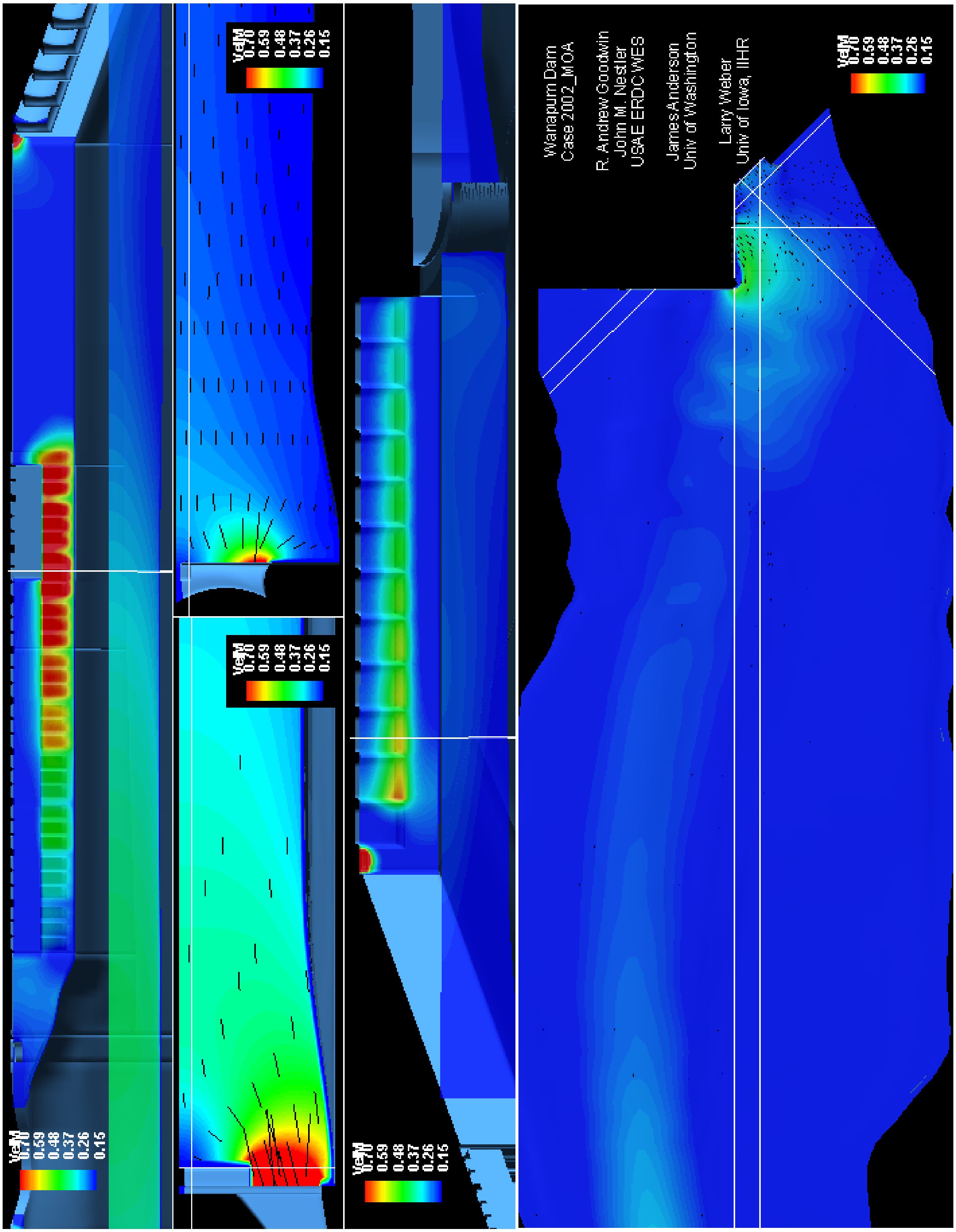

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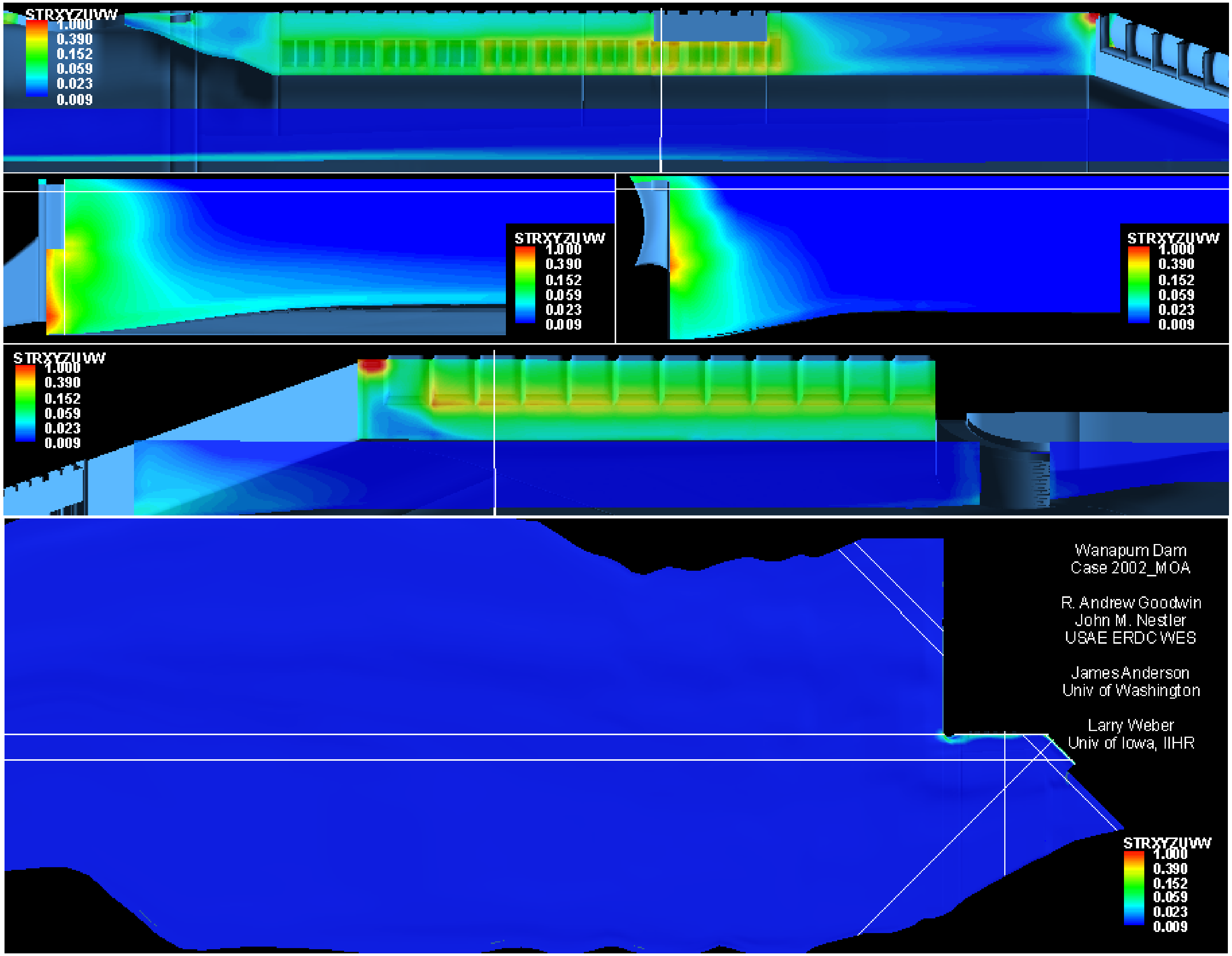

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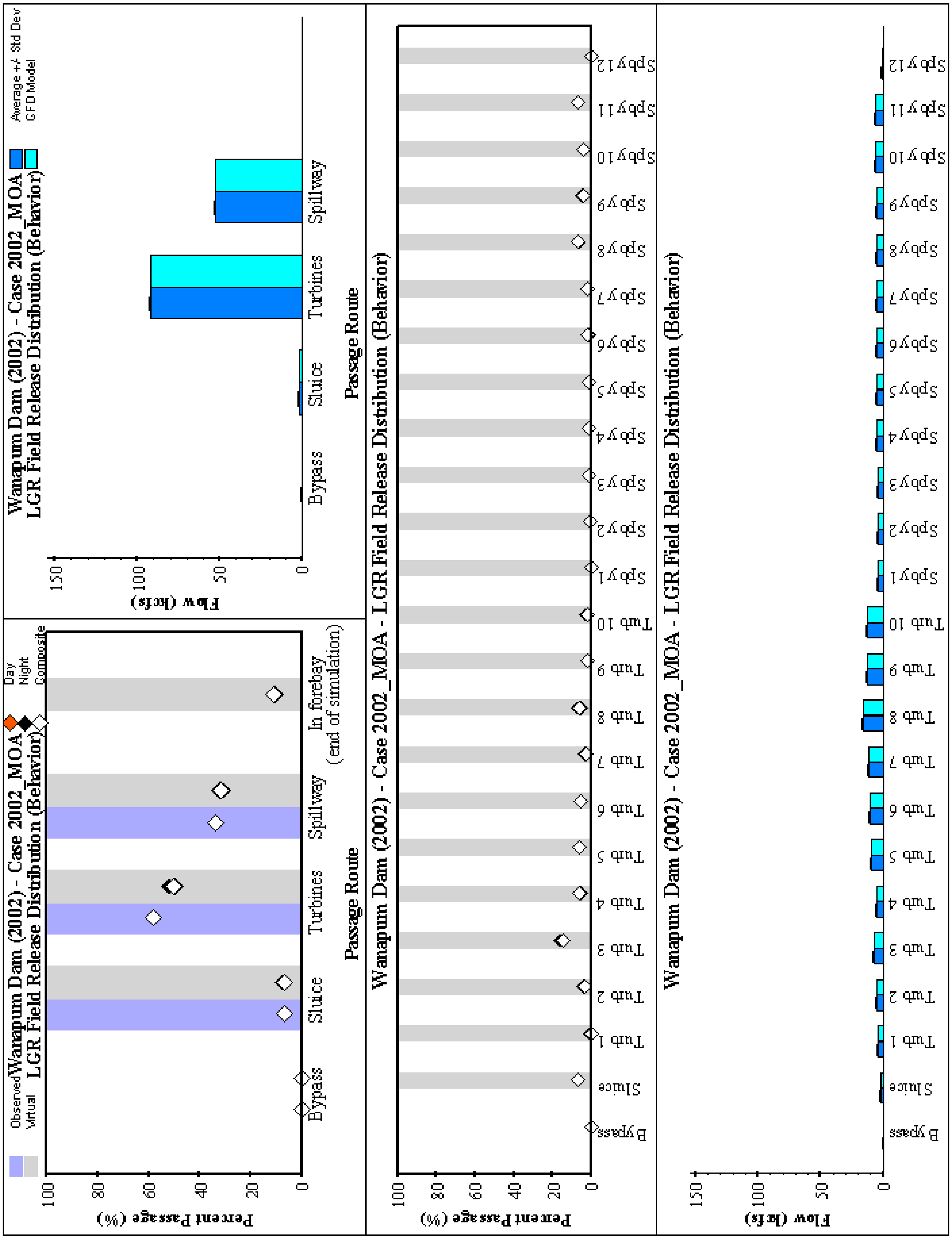

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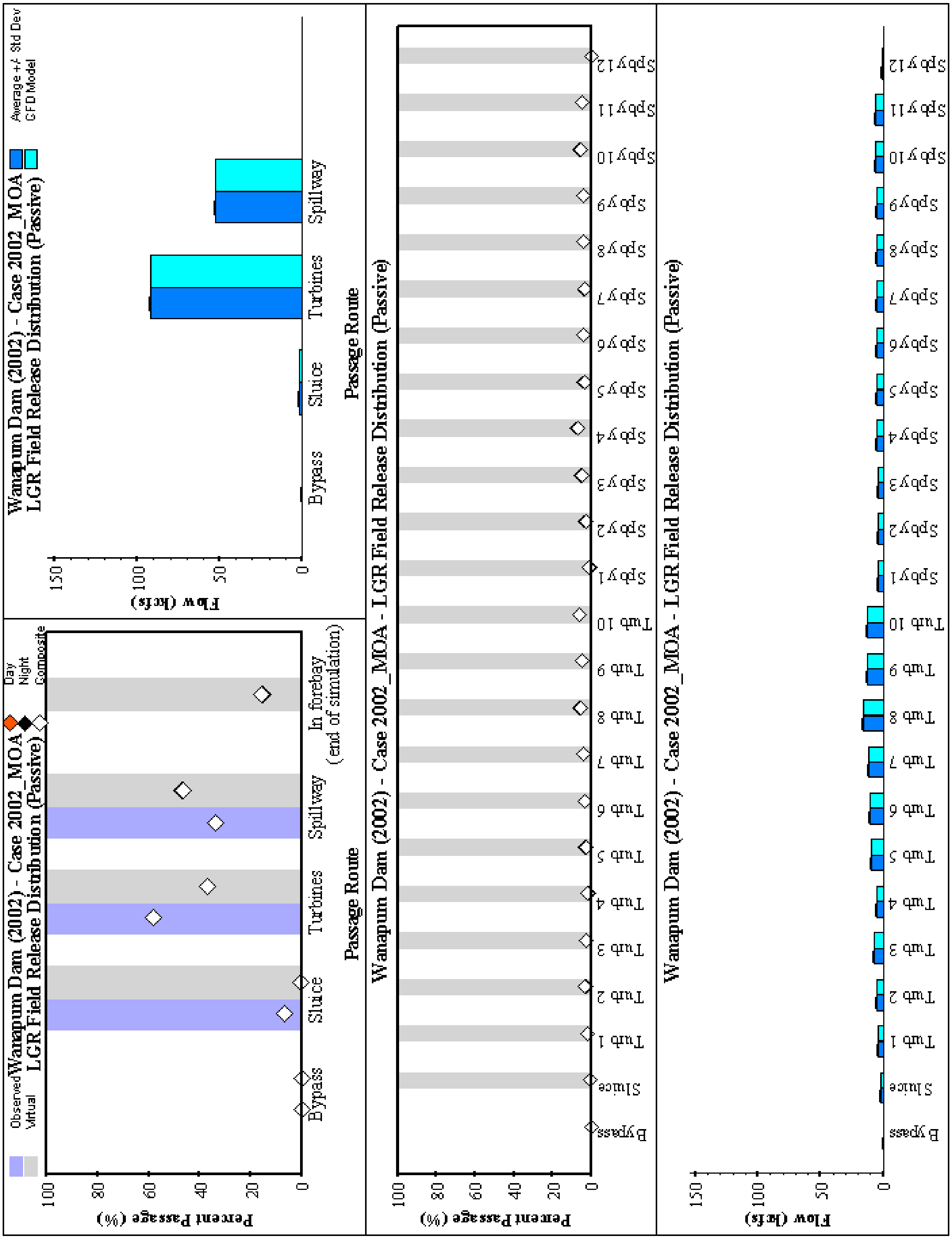

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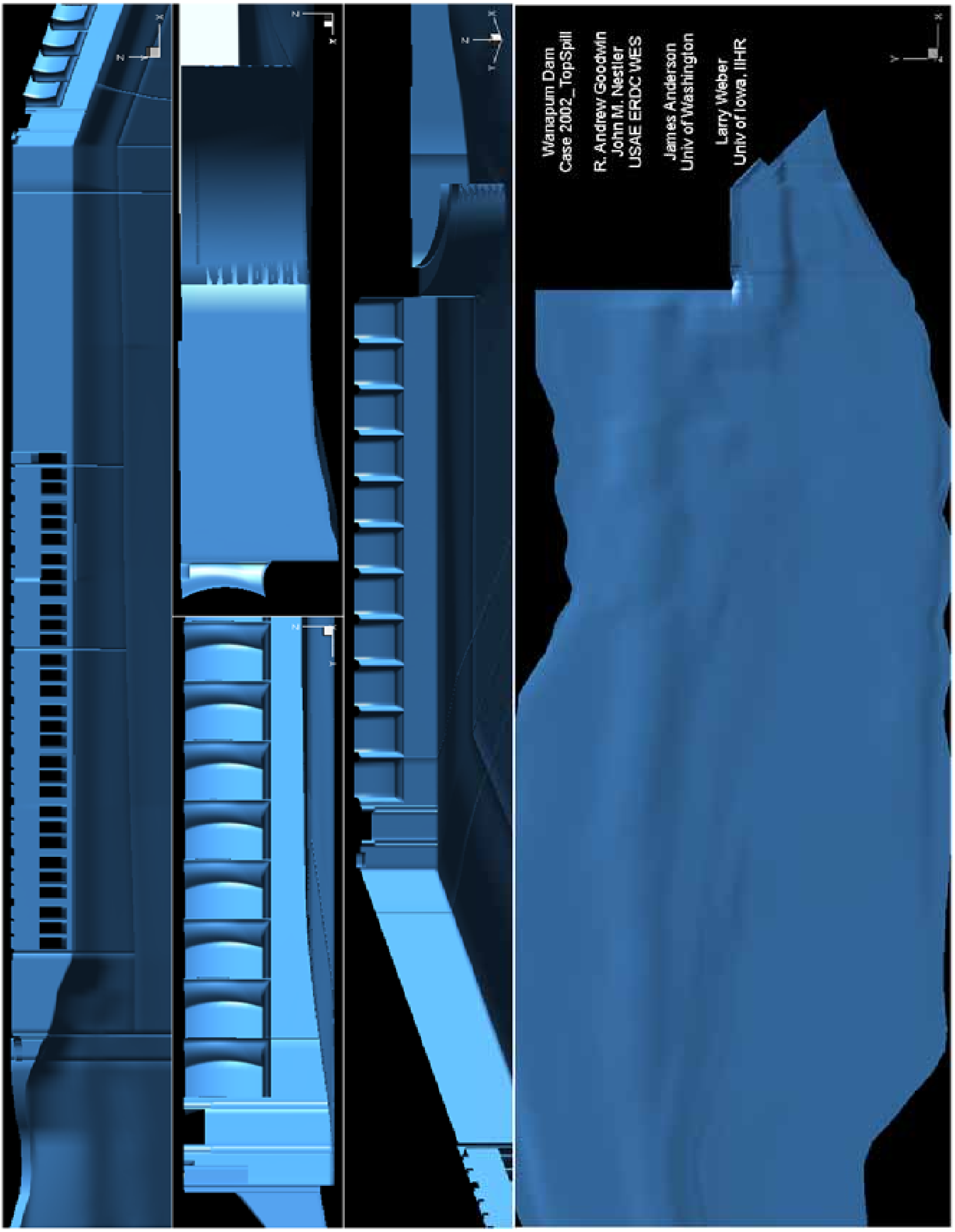
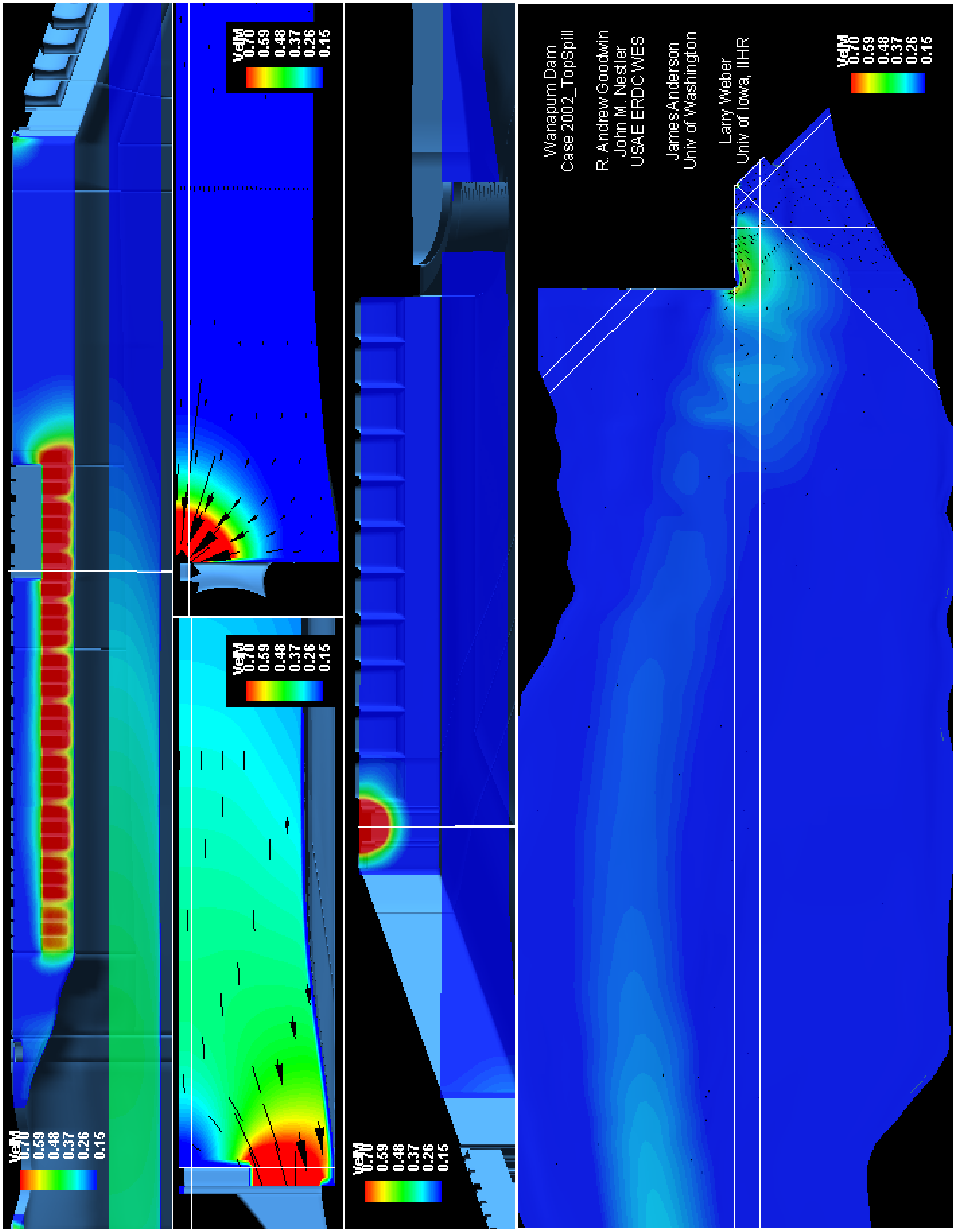


Figure A5. Wanapum Dam, Case 2002_TopSpill (Sheet 1 of 5)



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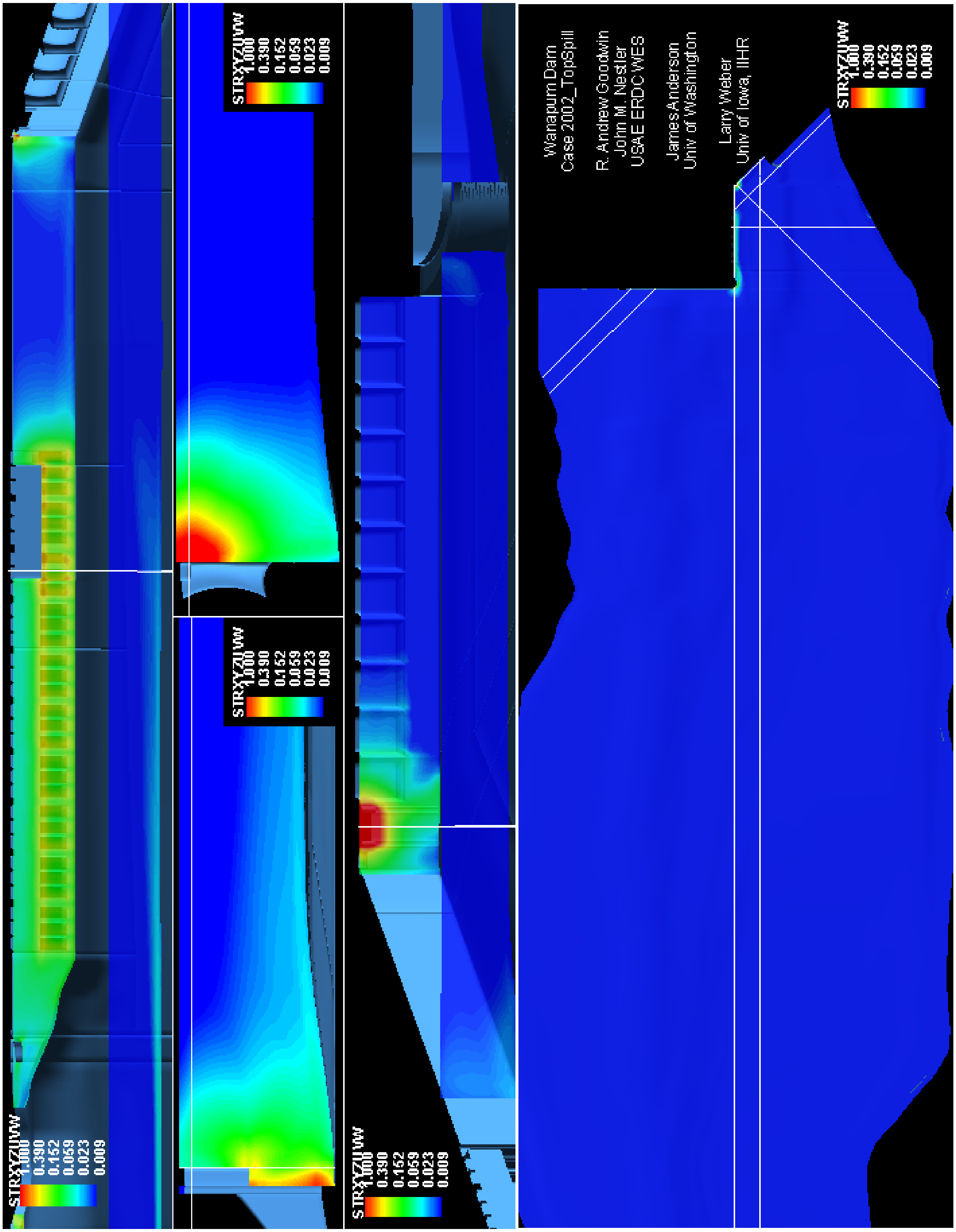

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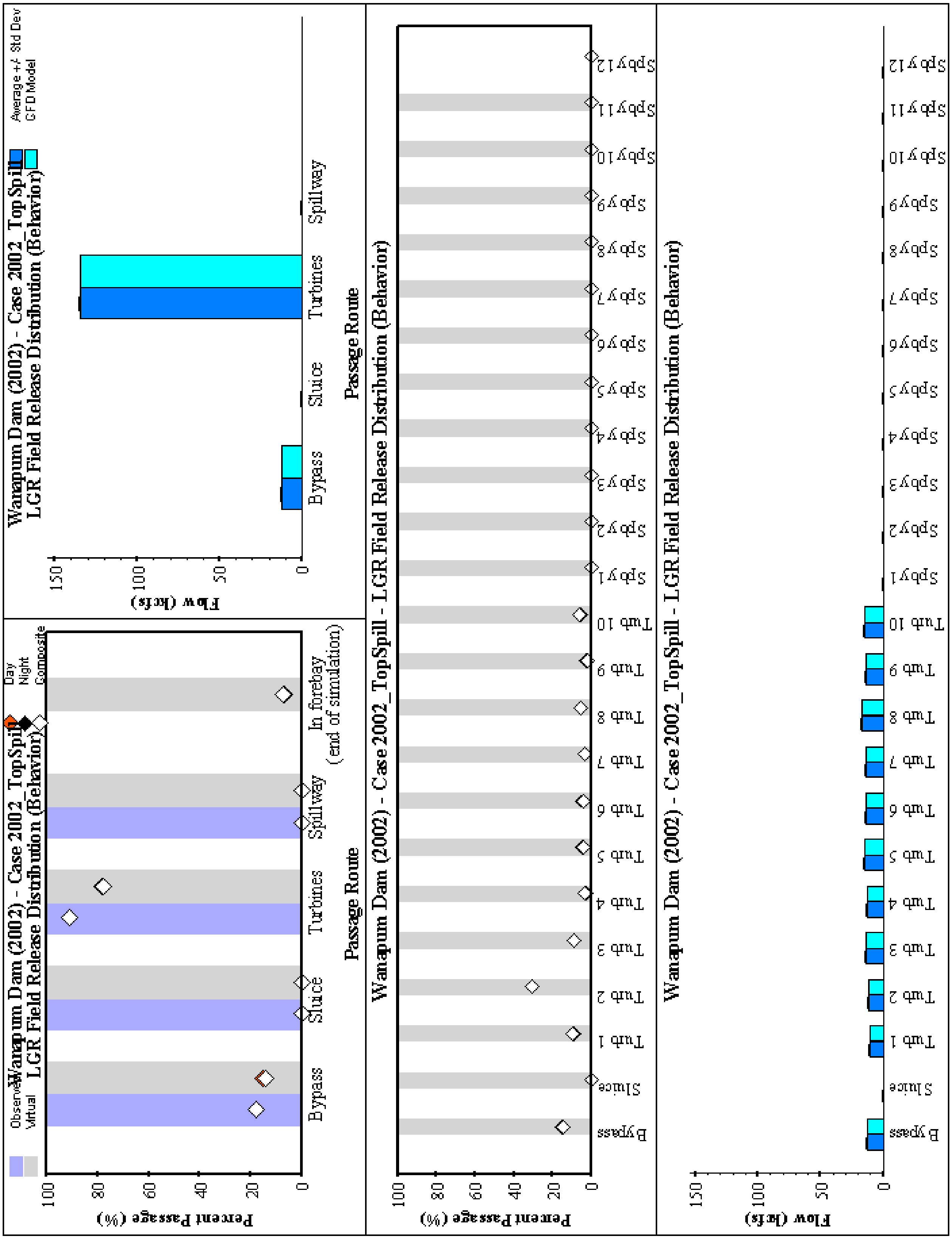

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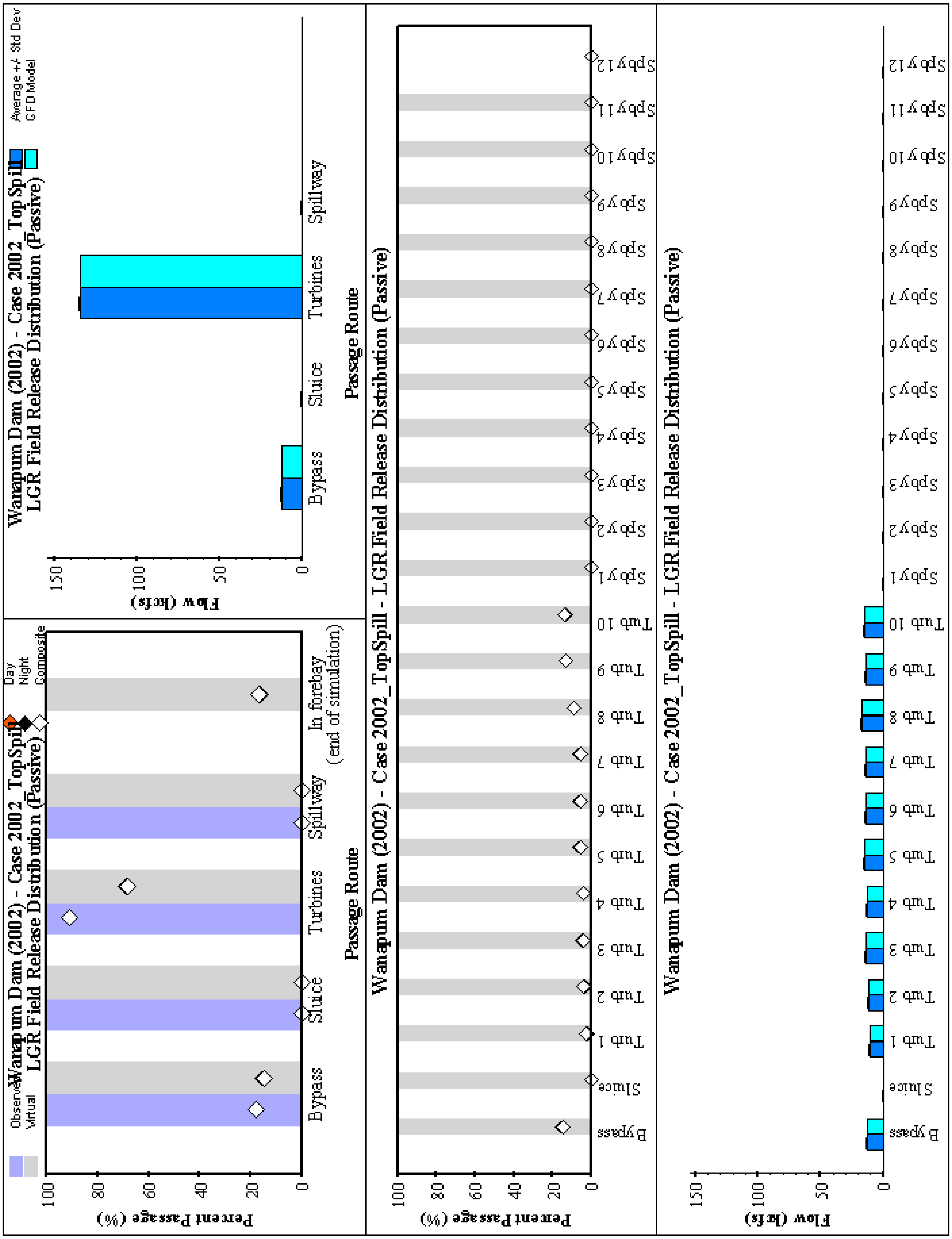

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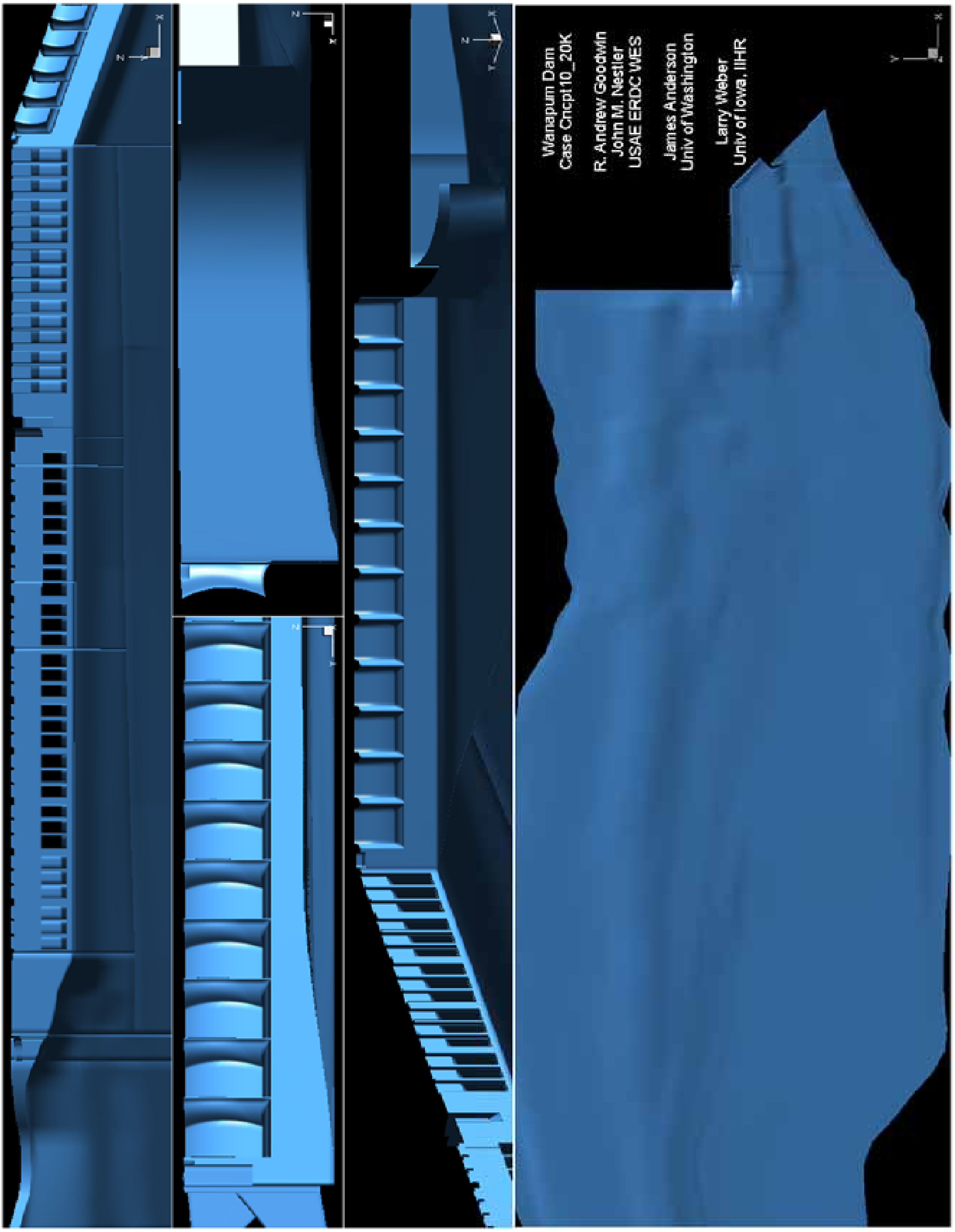
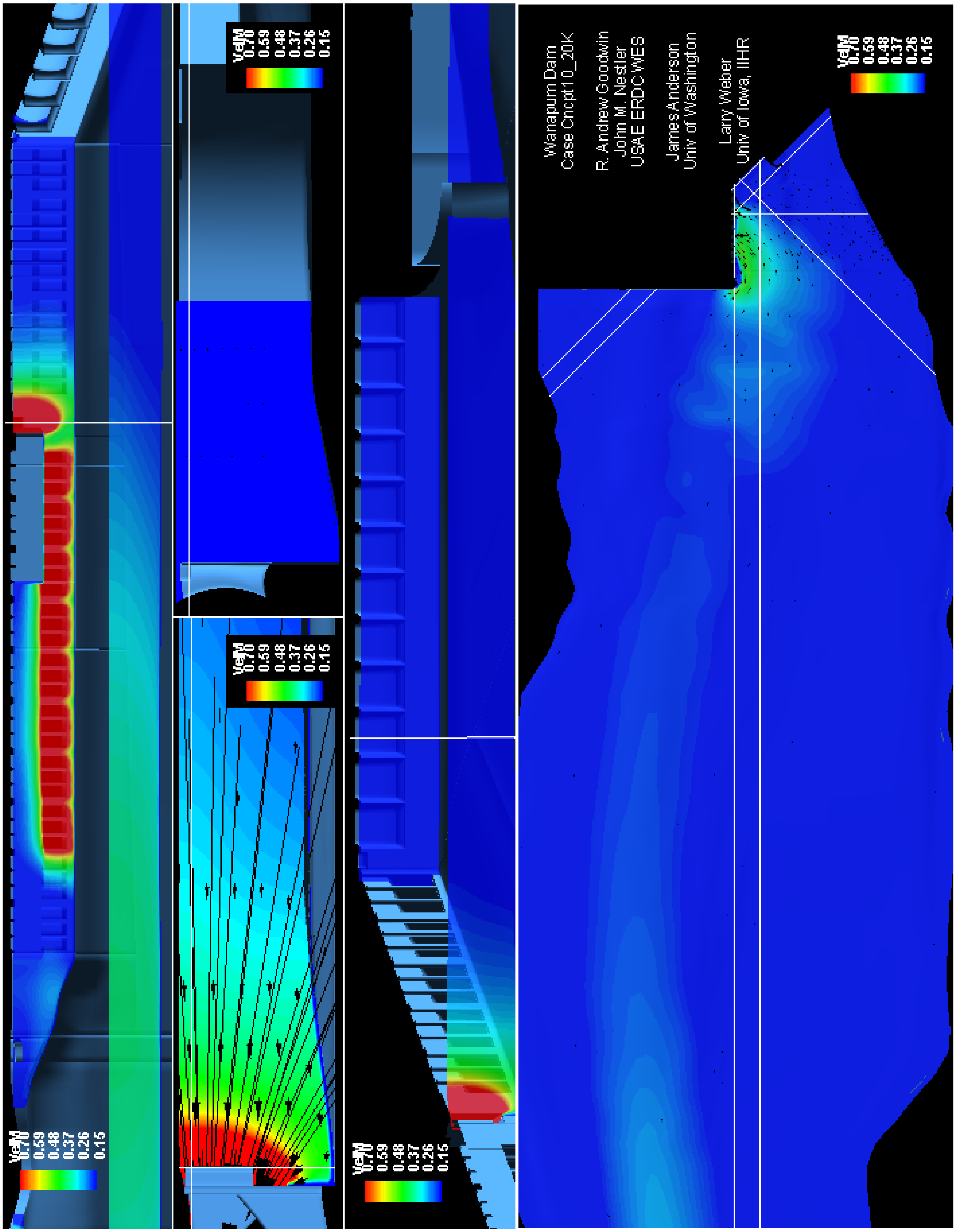


Figure A6. Wanapum Dam, Case Cncpt10_20K (Sheet 1 of 5)



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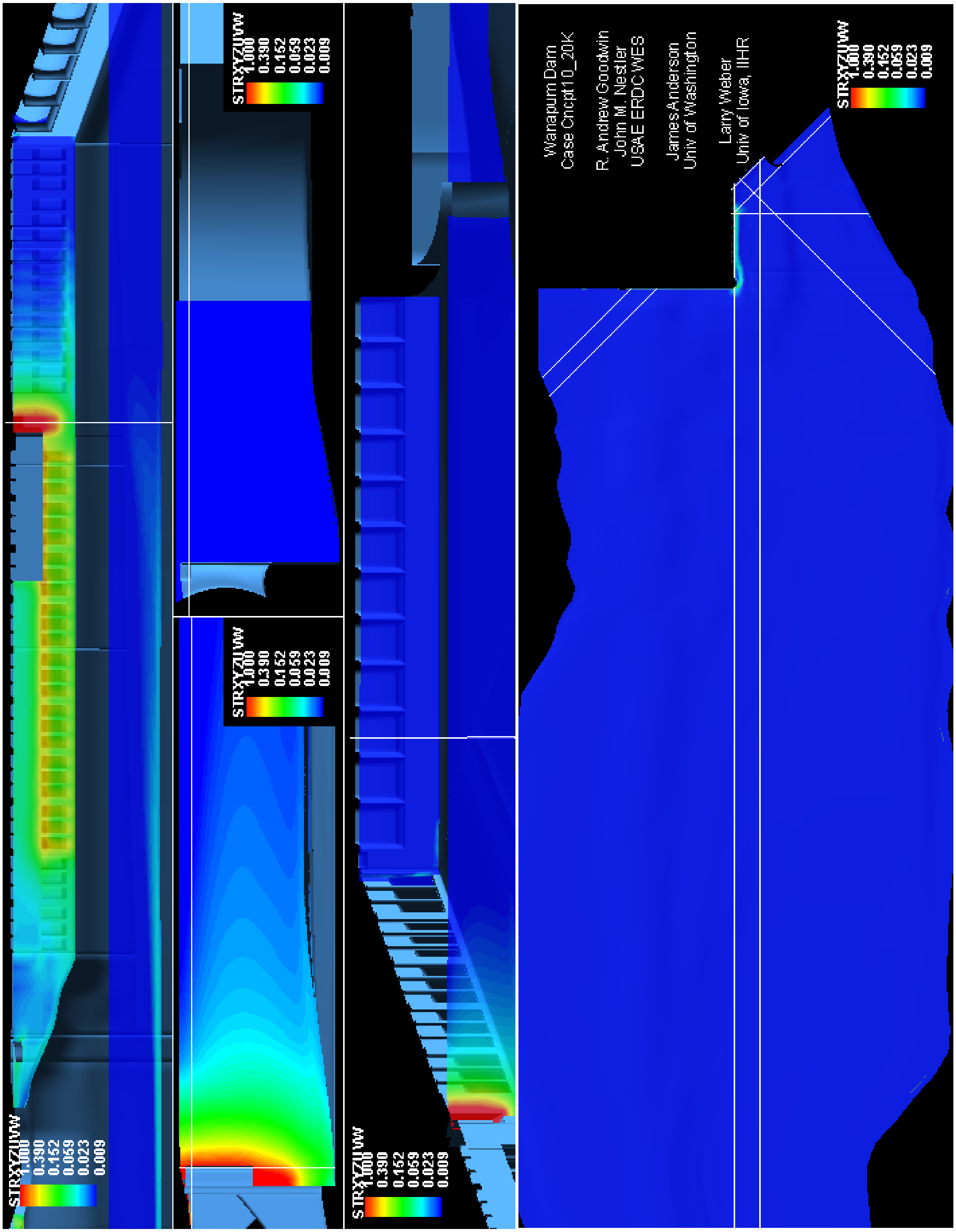

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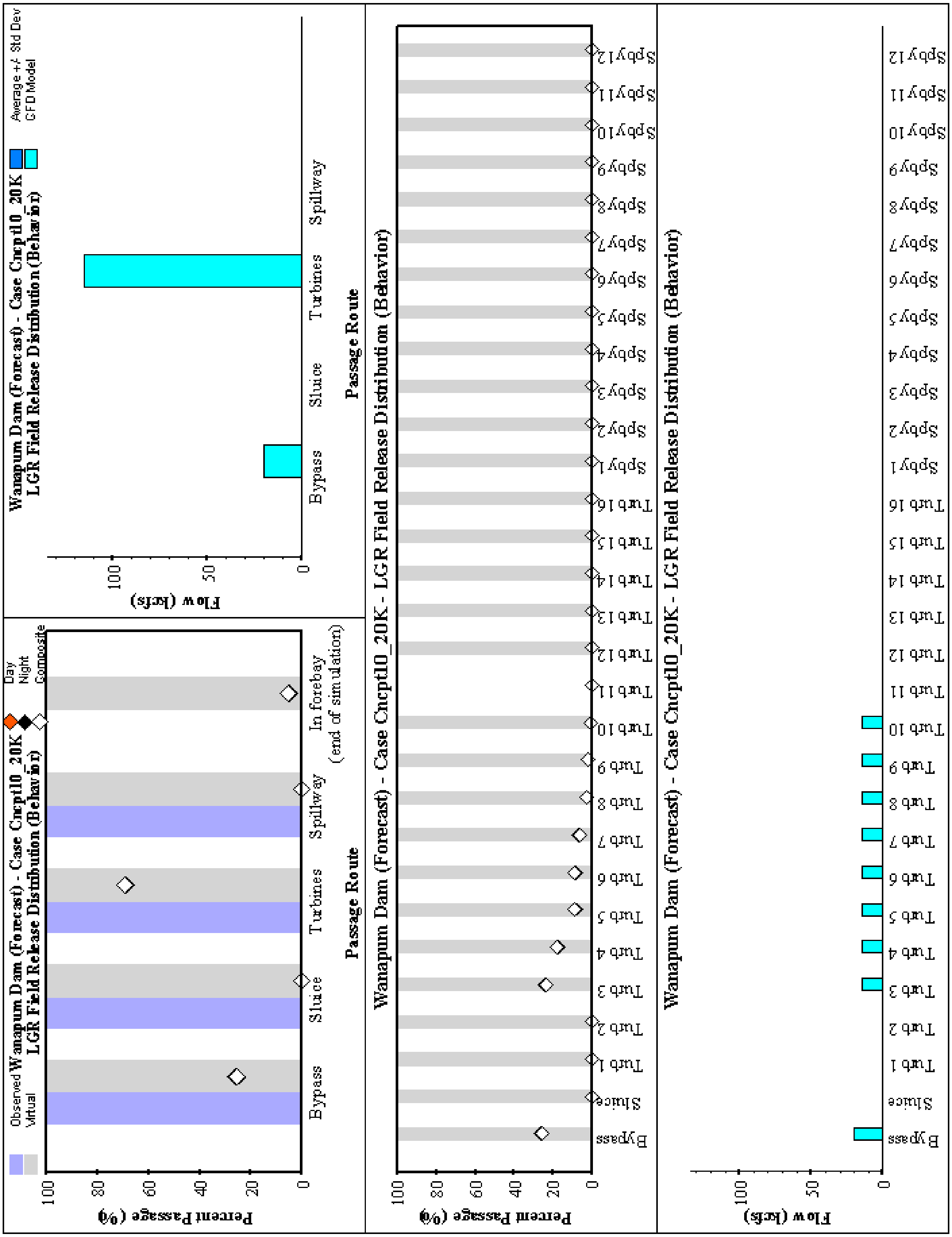

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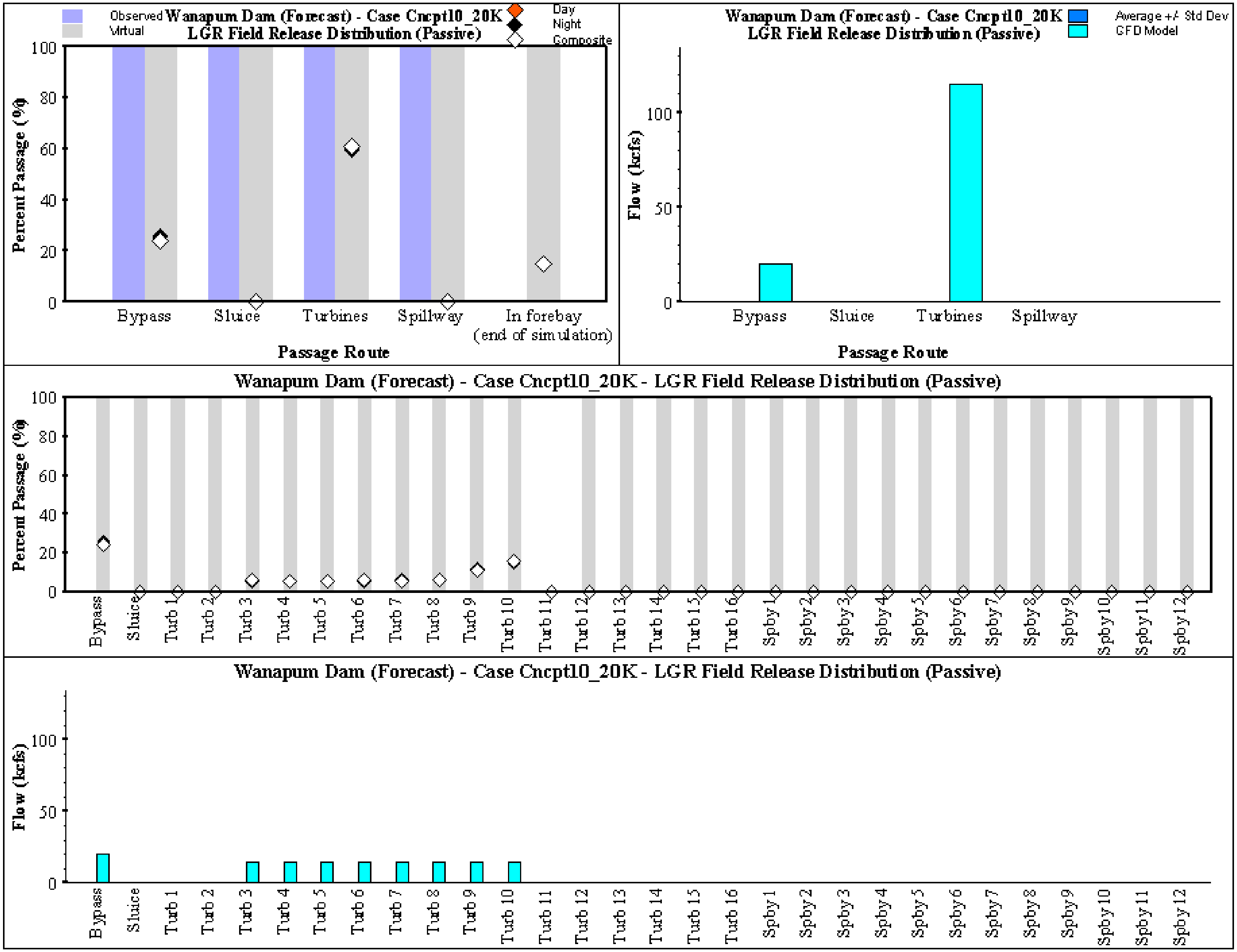

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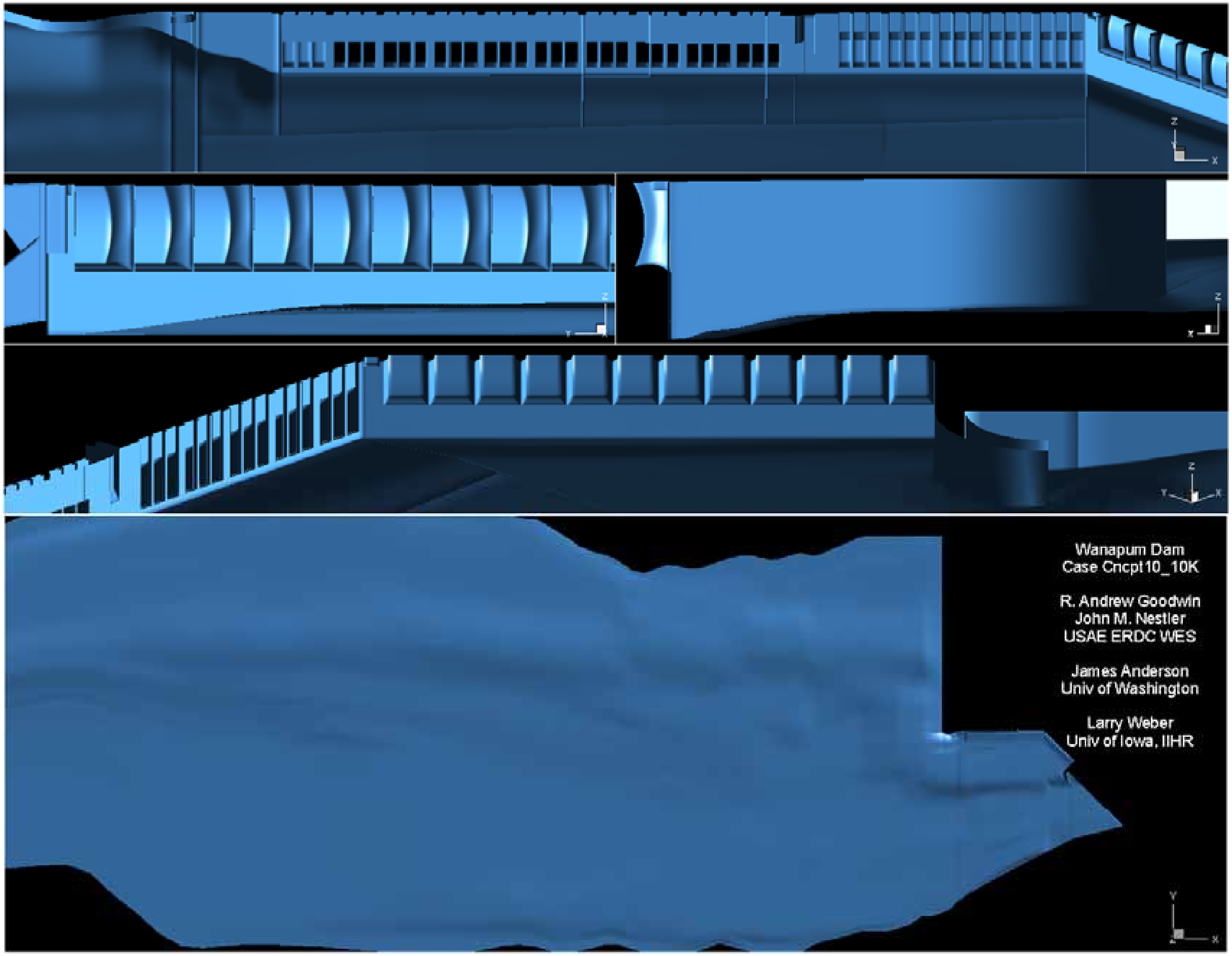
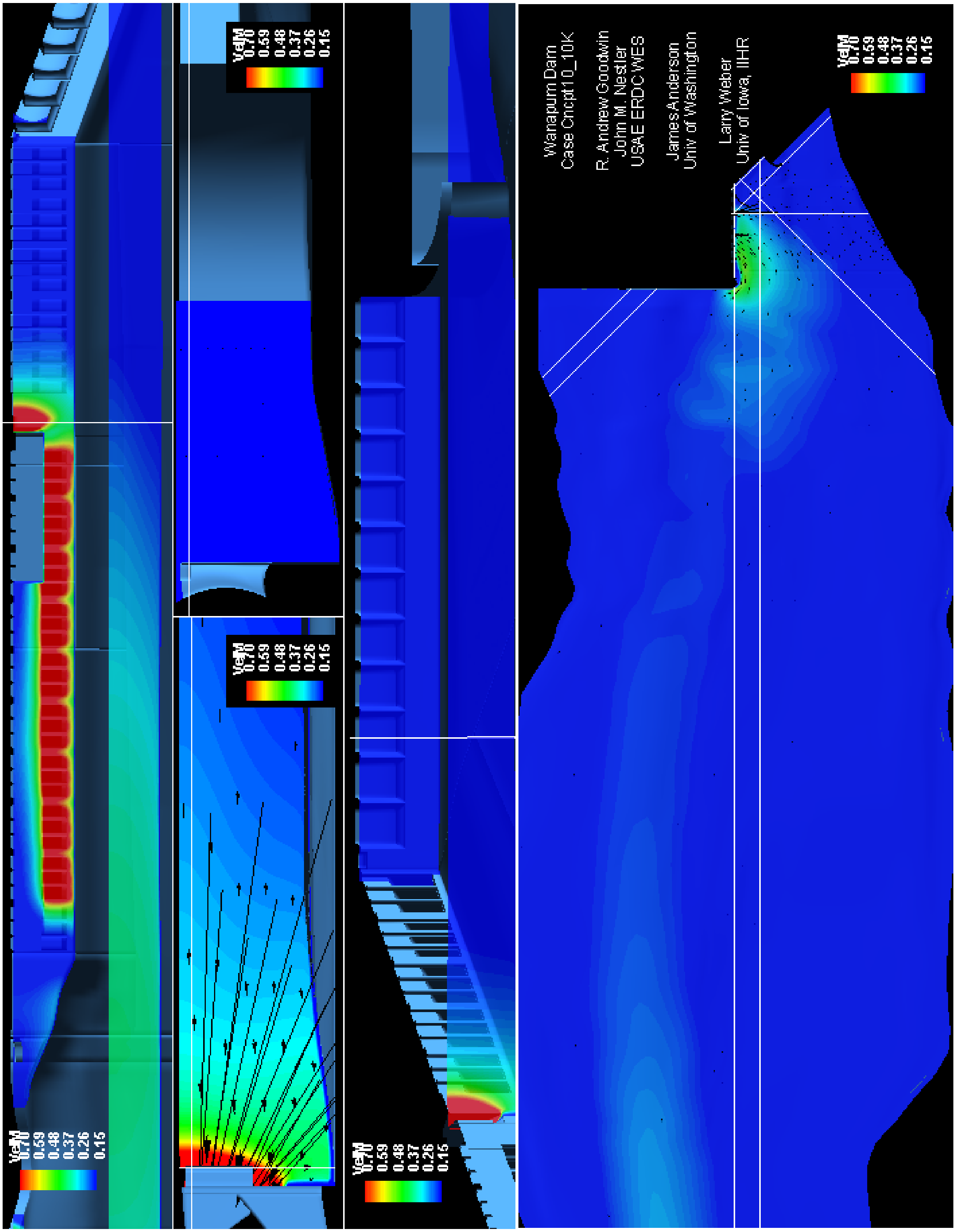


Figure A7. Wanapum Dam, Case Cncpt10_10K (Sheet 1 of 5)



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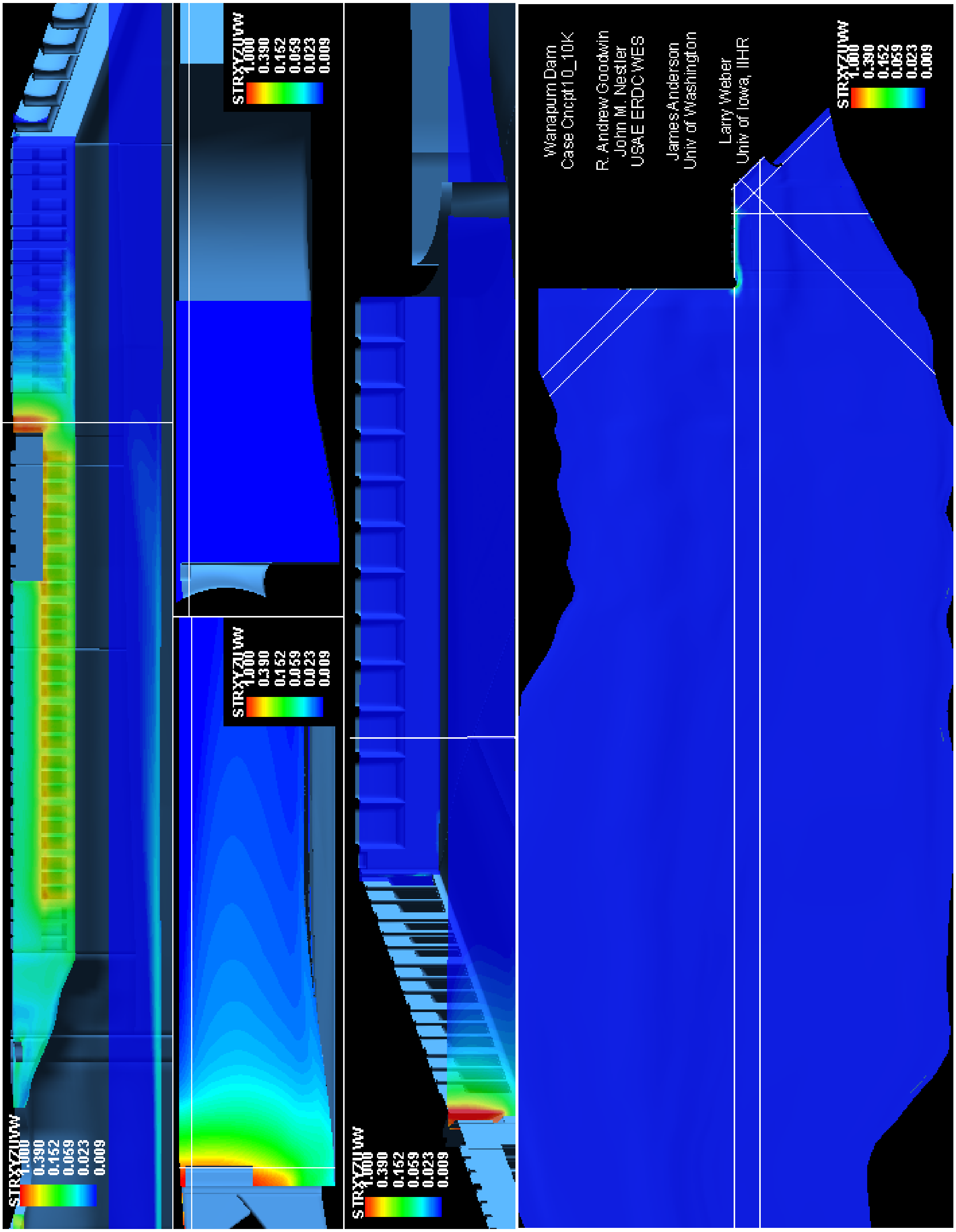

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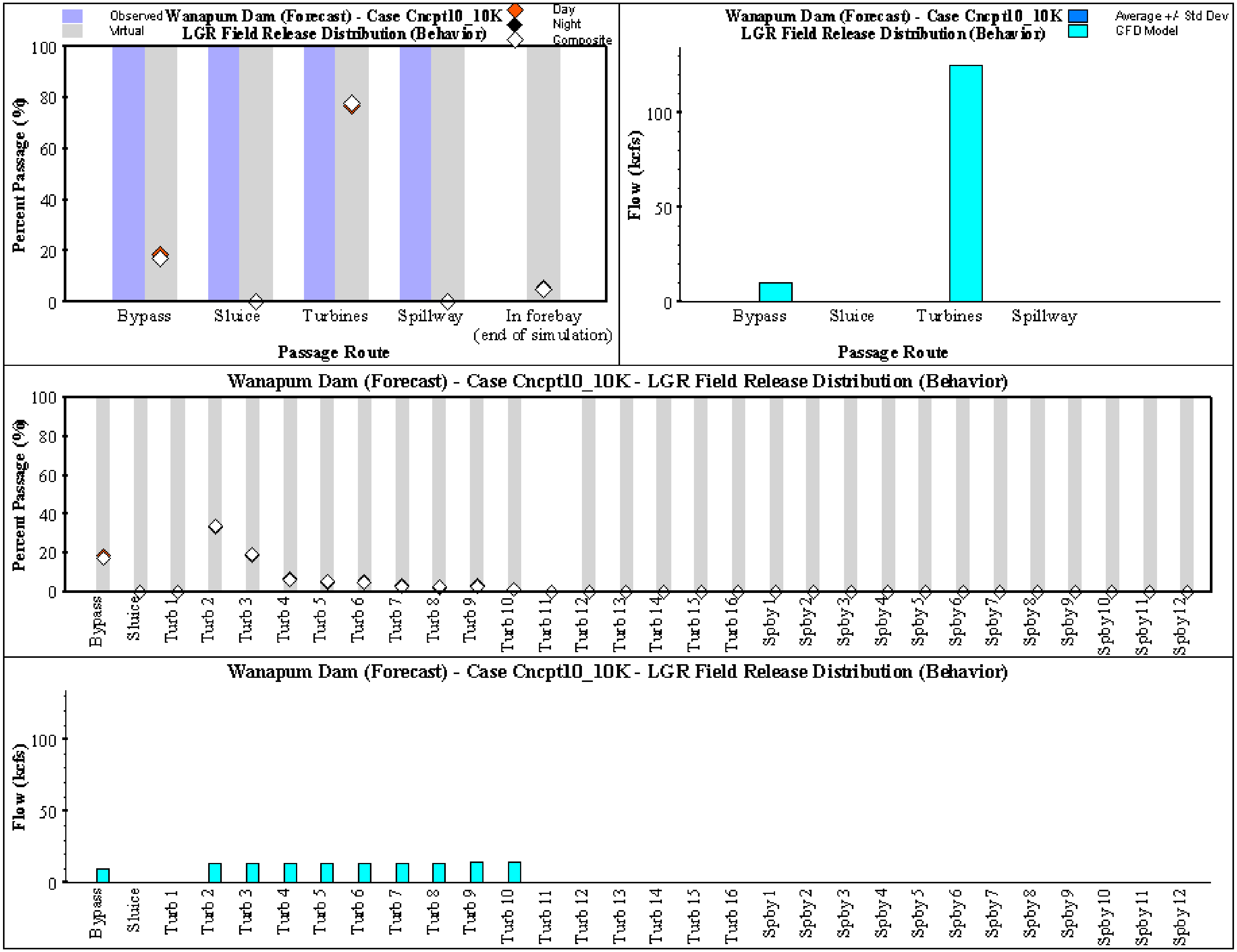

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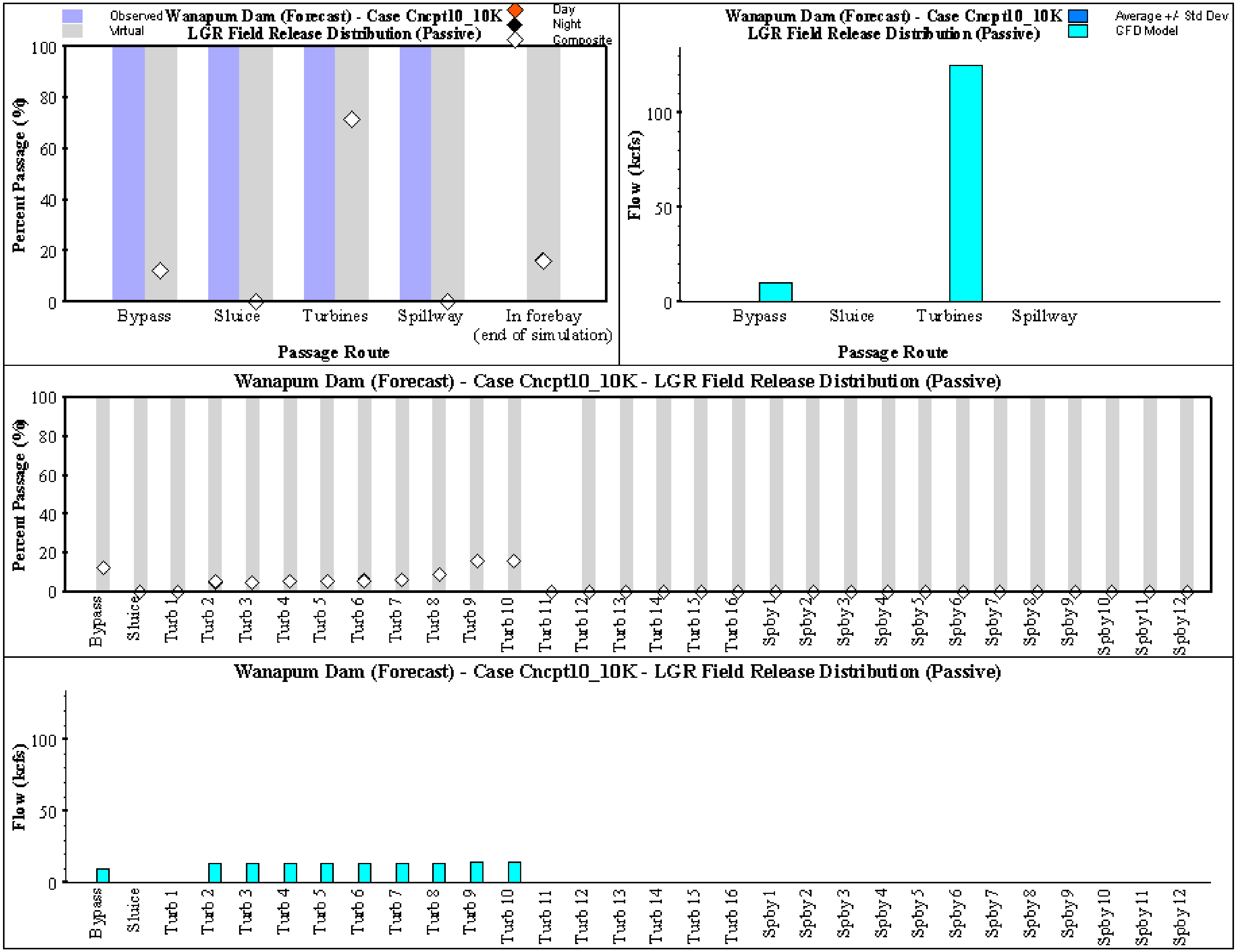

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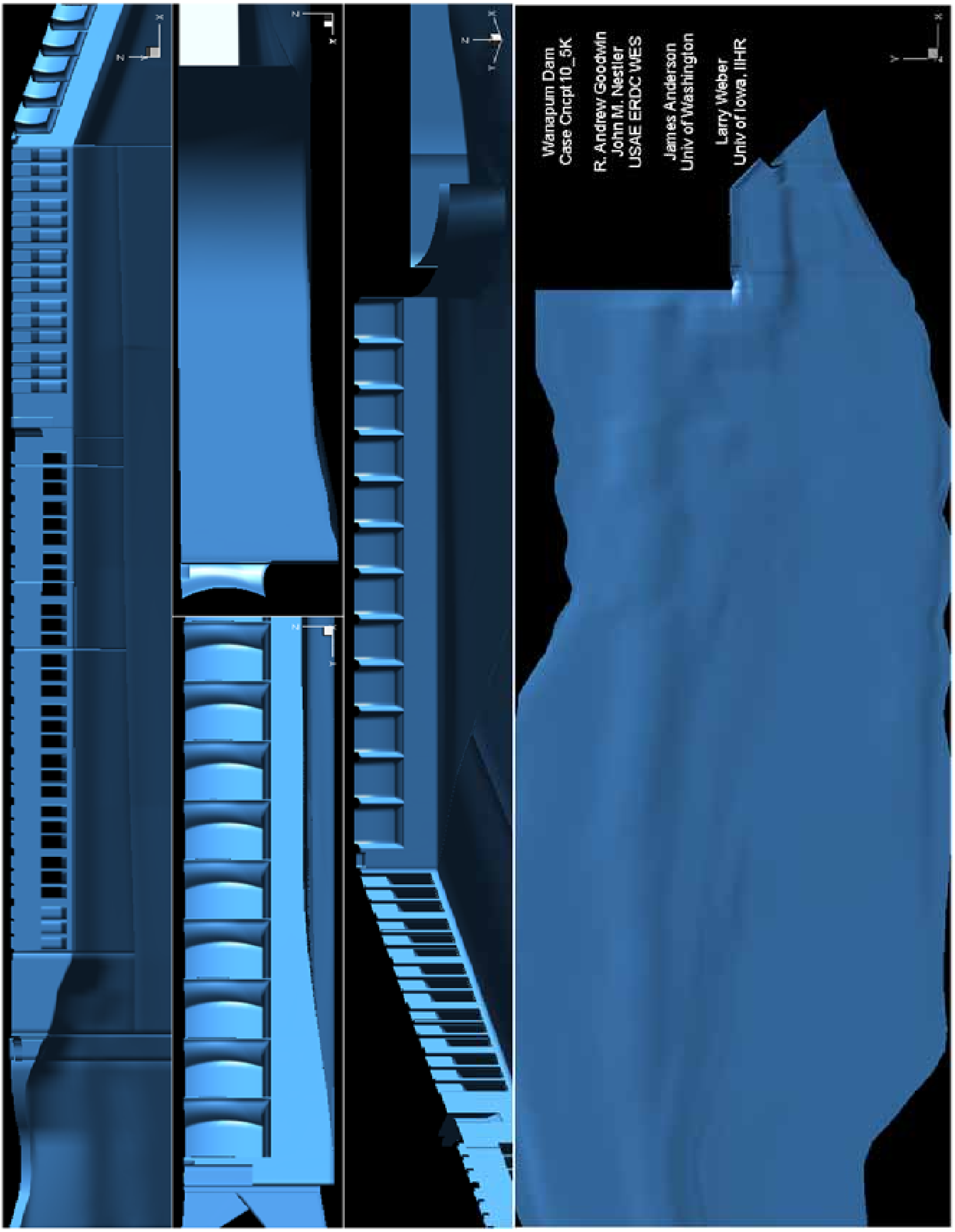
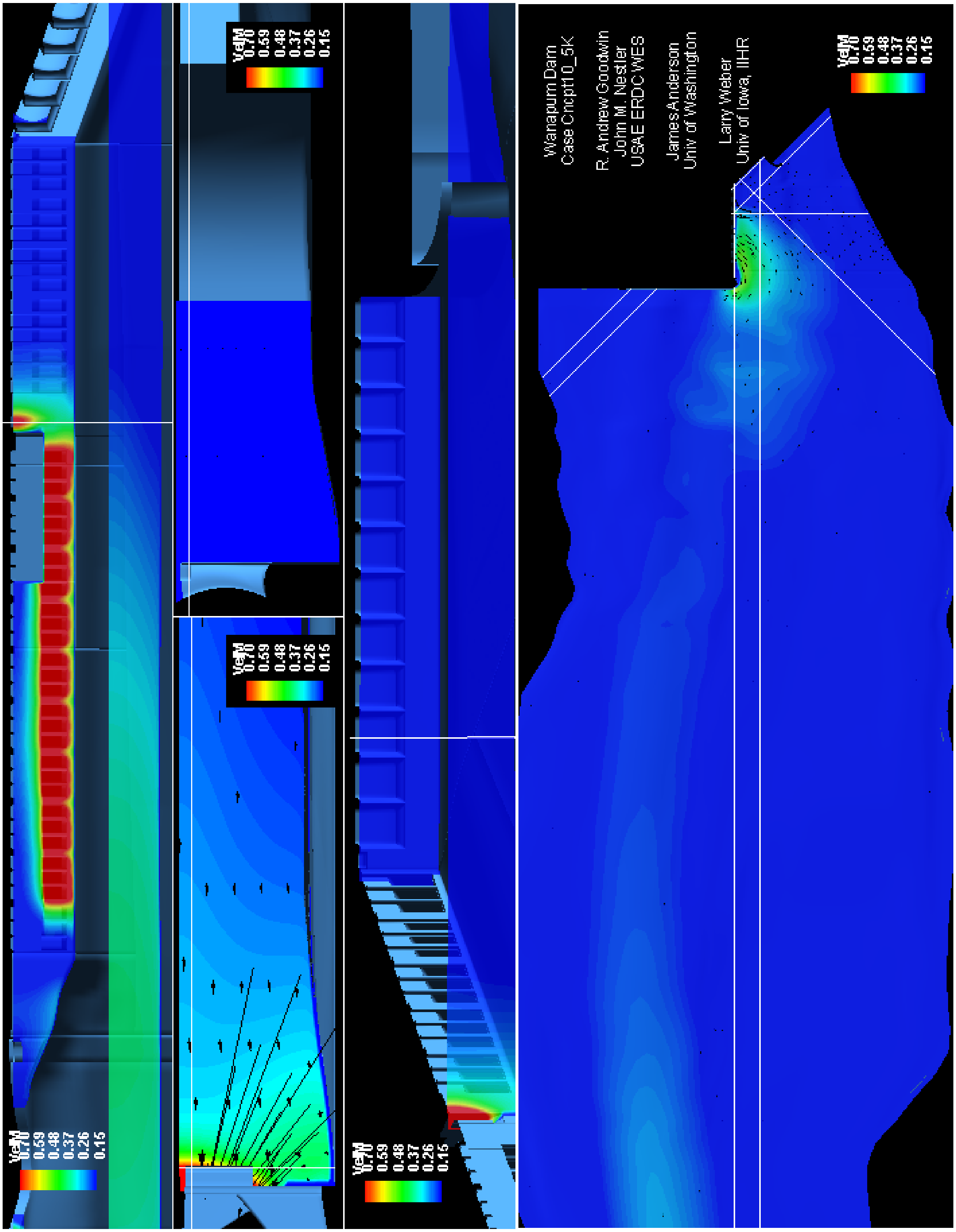


Figure A8. Wanapum Dam, Case Cncpt10_5K (Sheet 1 of 5)



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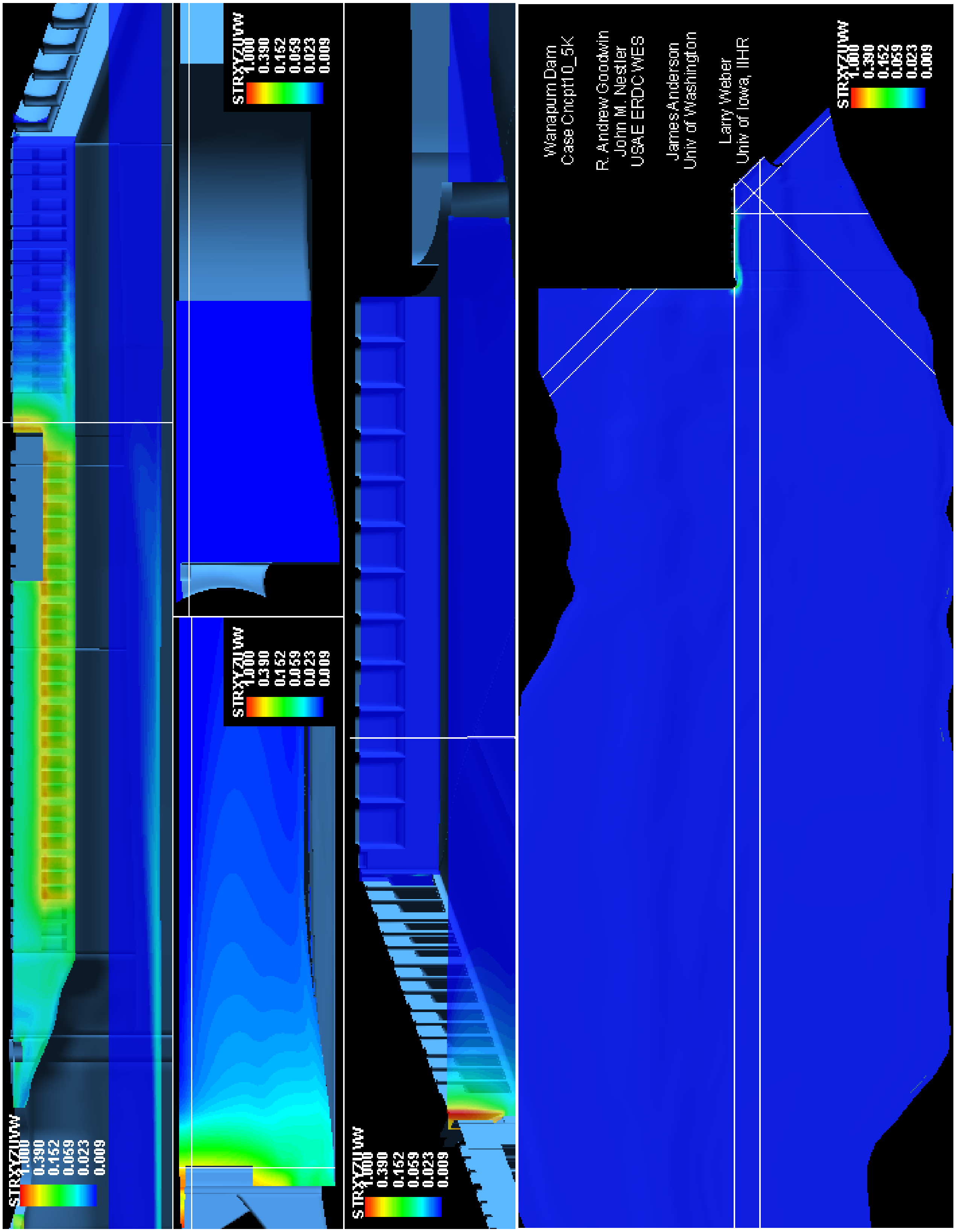

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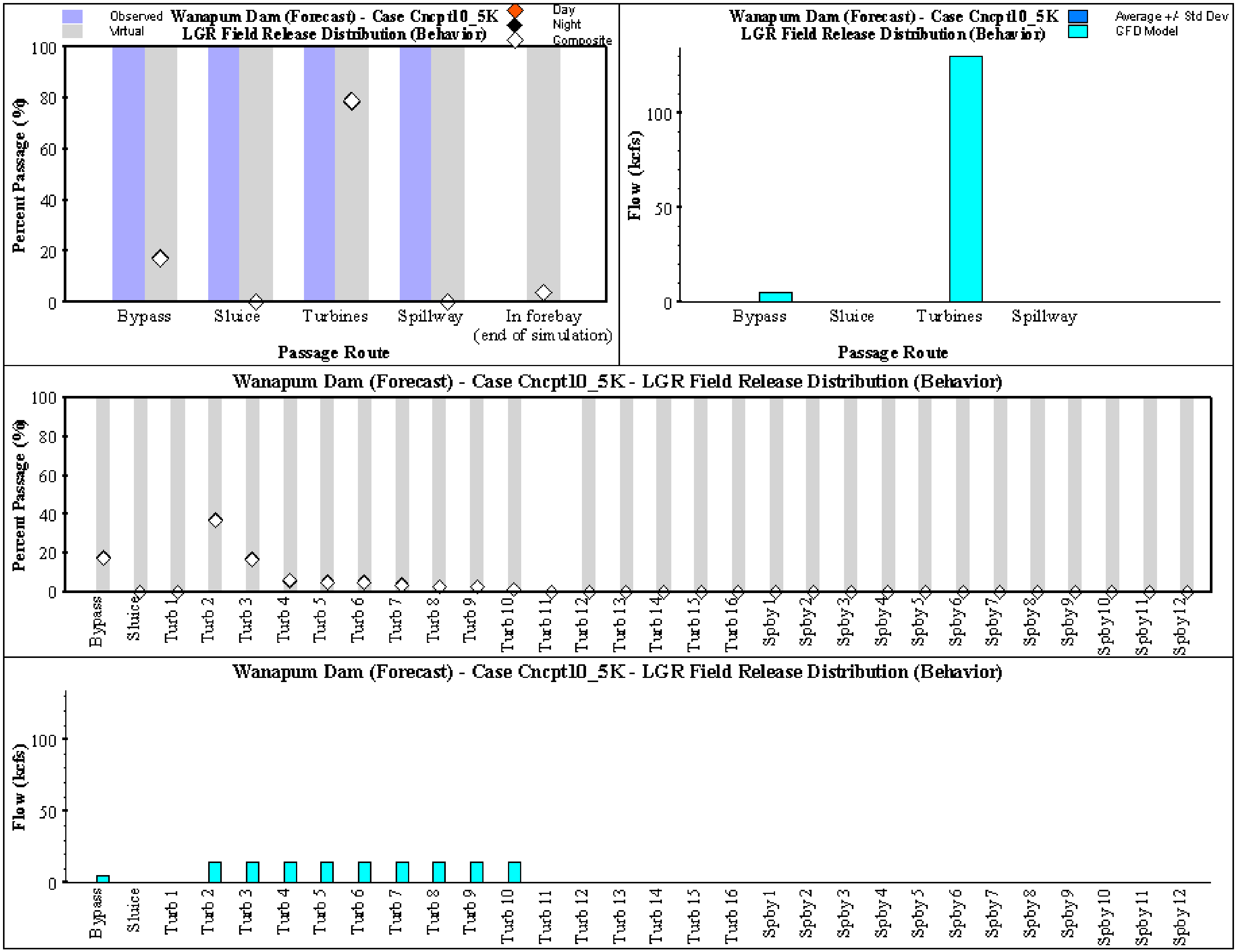

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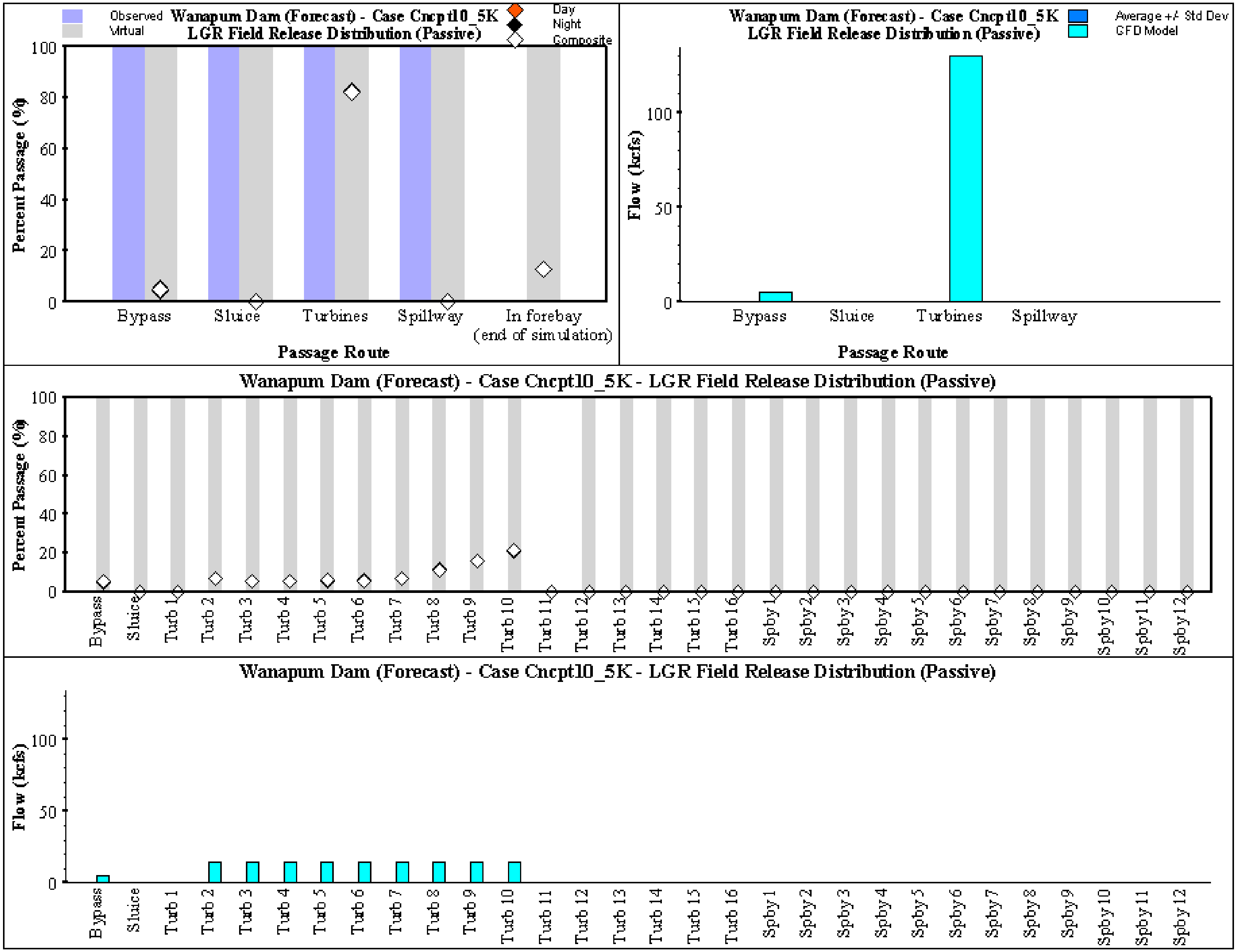

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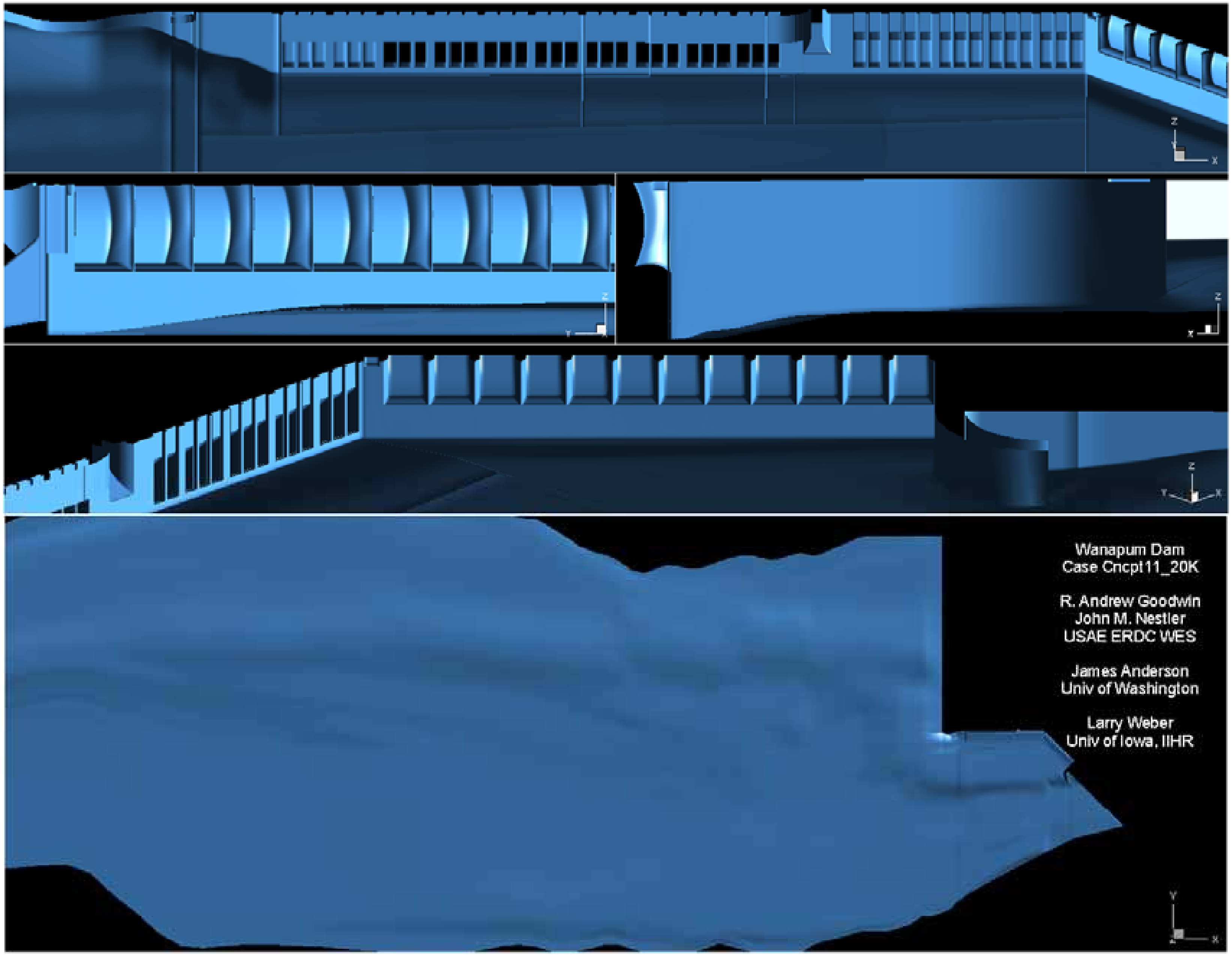
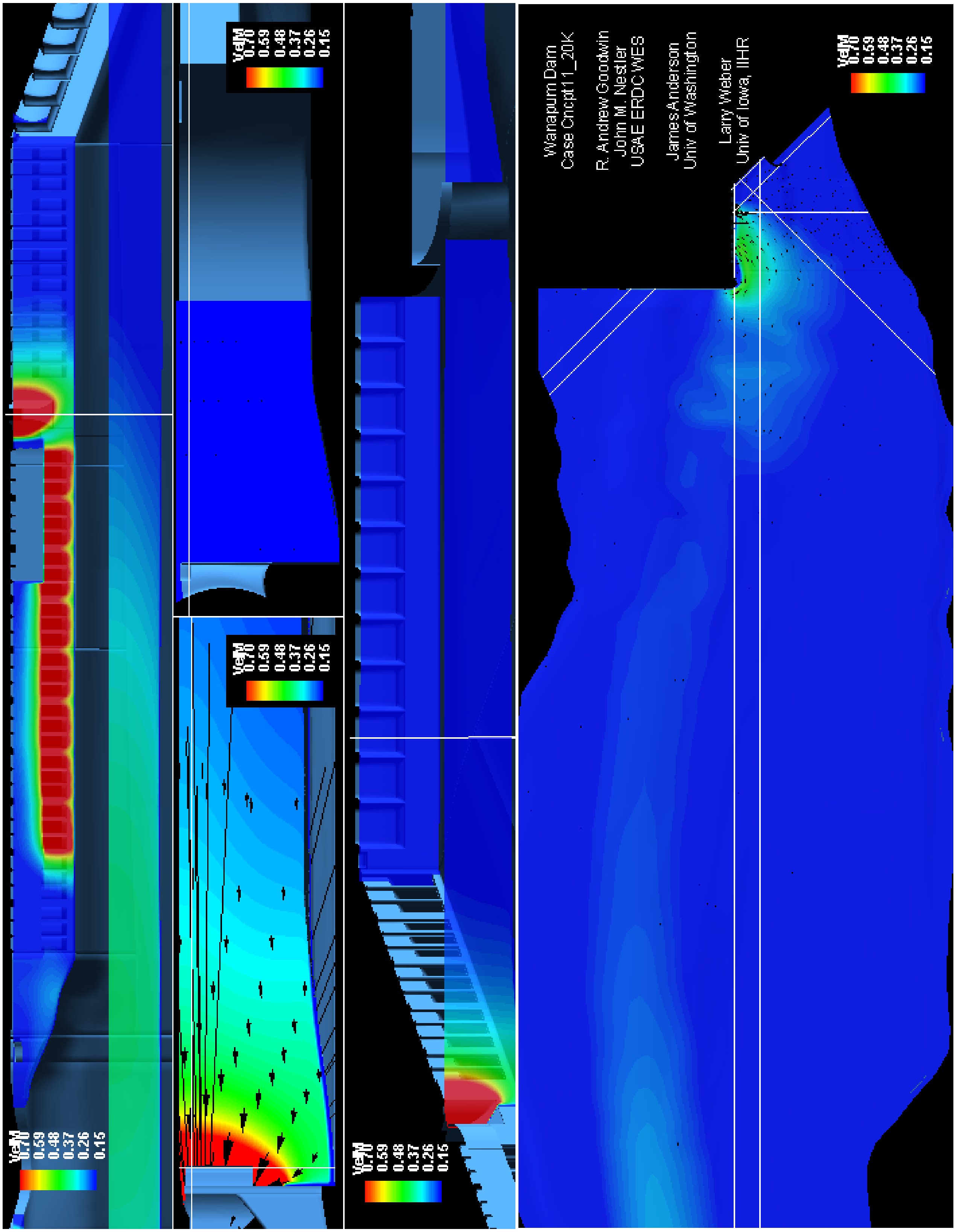


Figure A9.   Wanapum Dam, Case Cncpt11_20K (Sheet 1 of 5)



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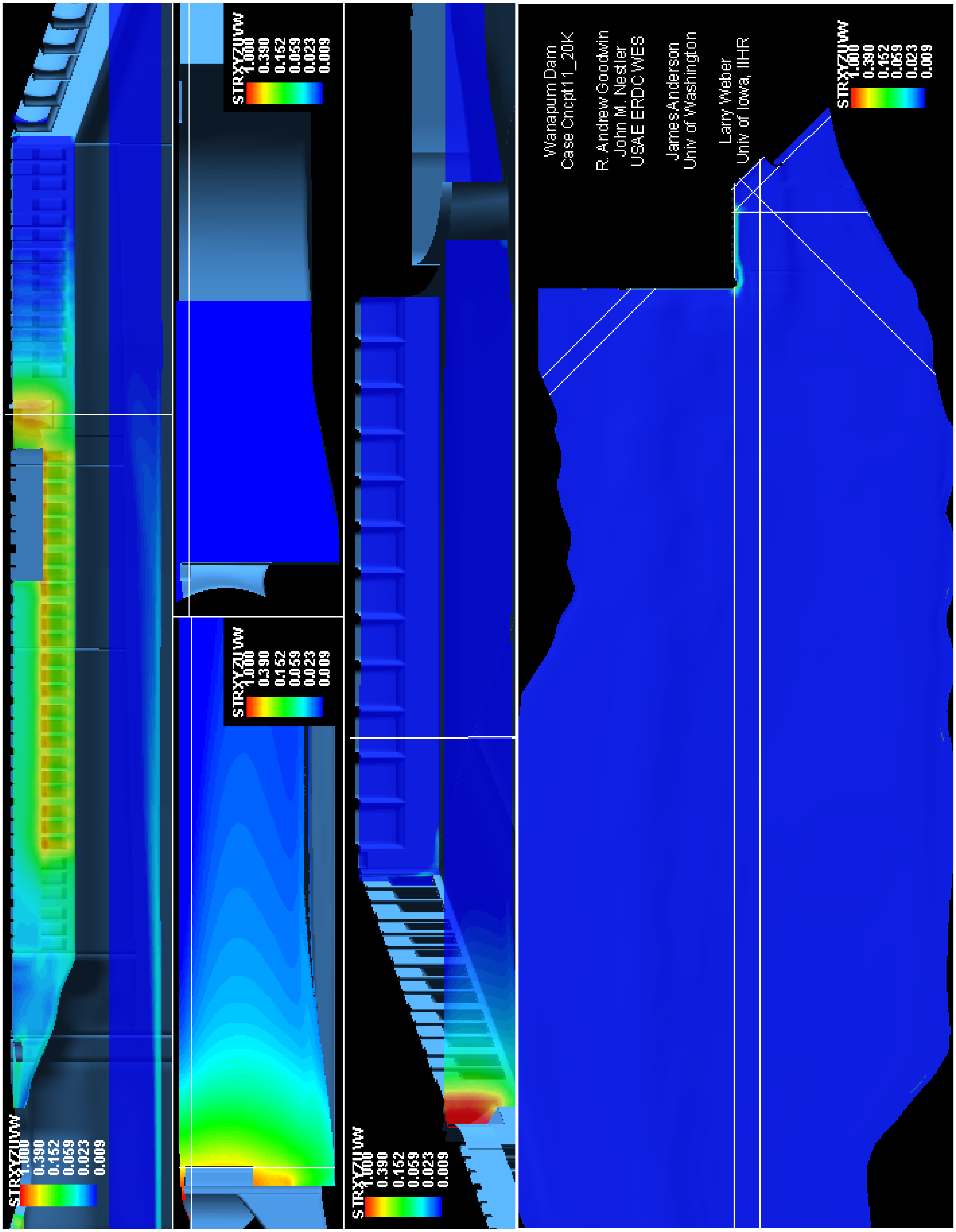

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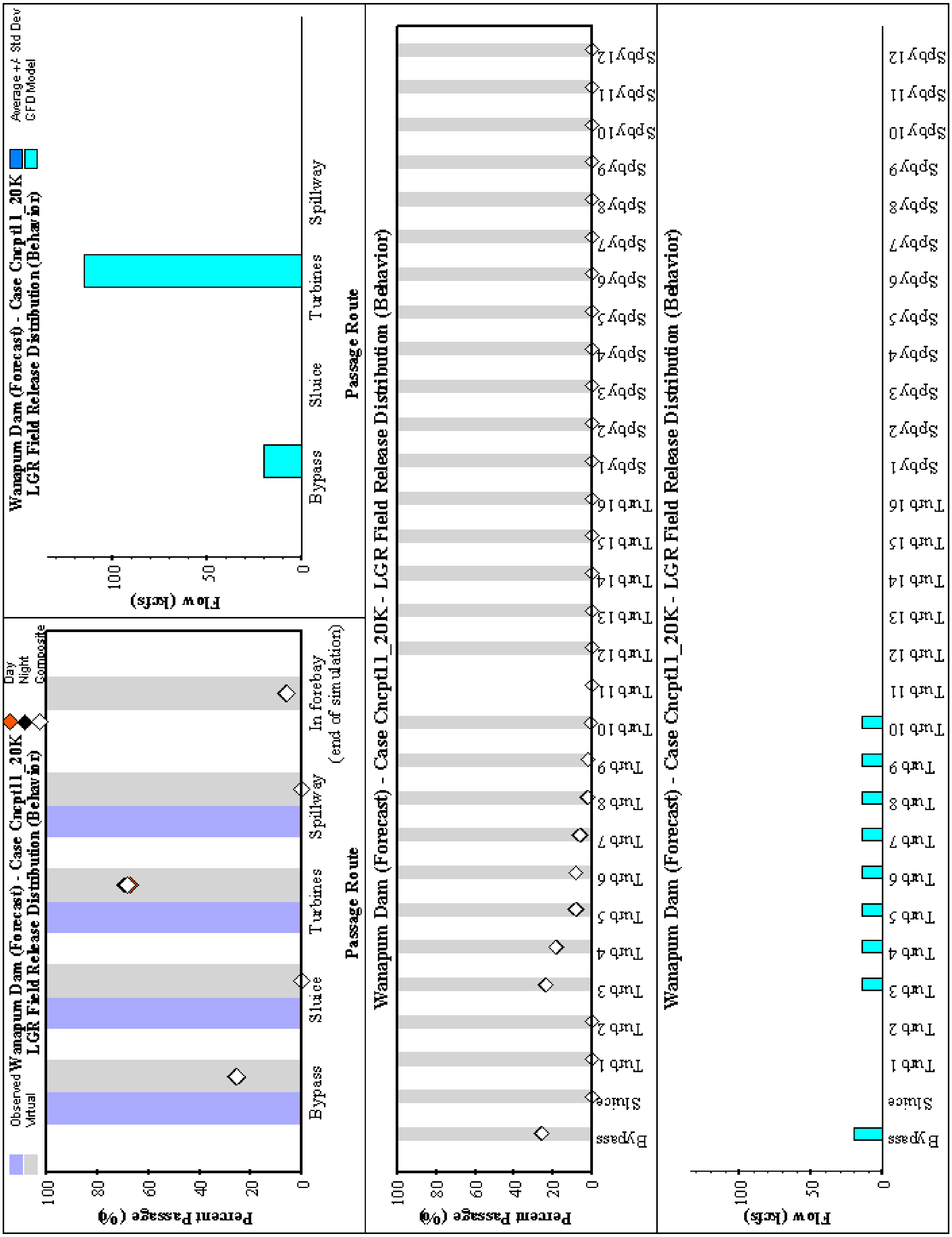

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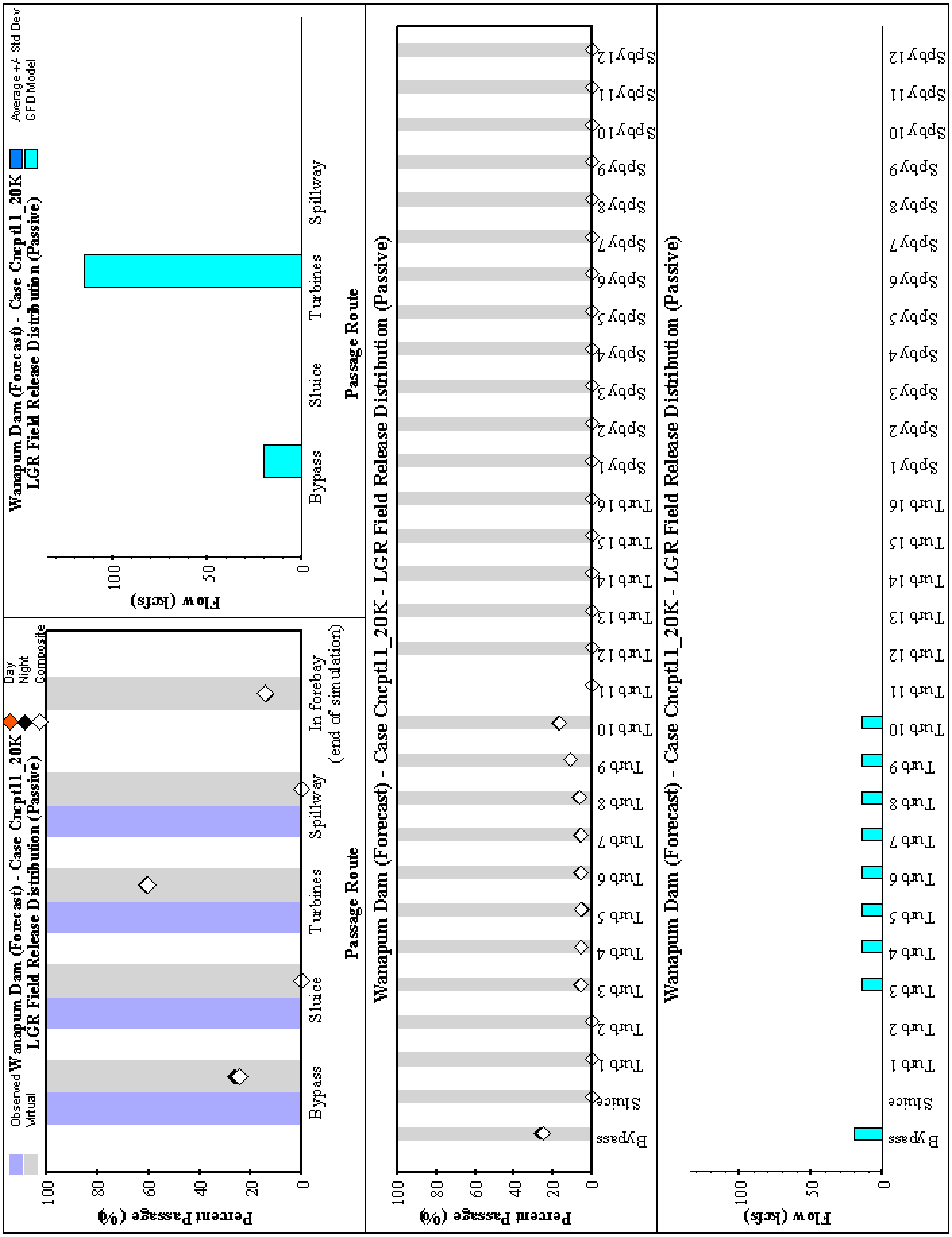

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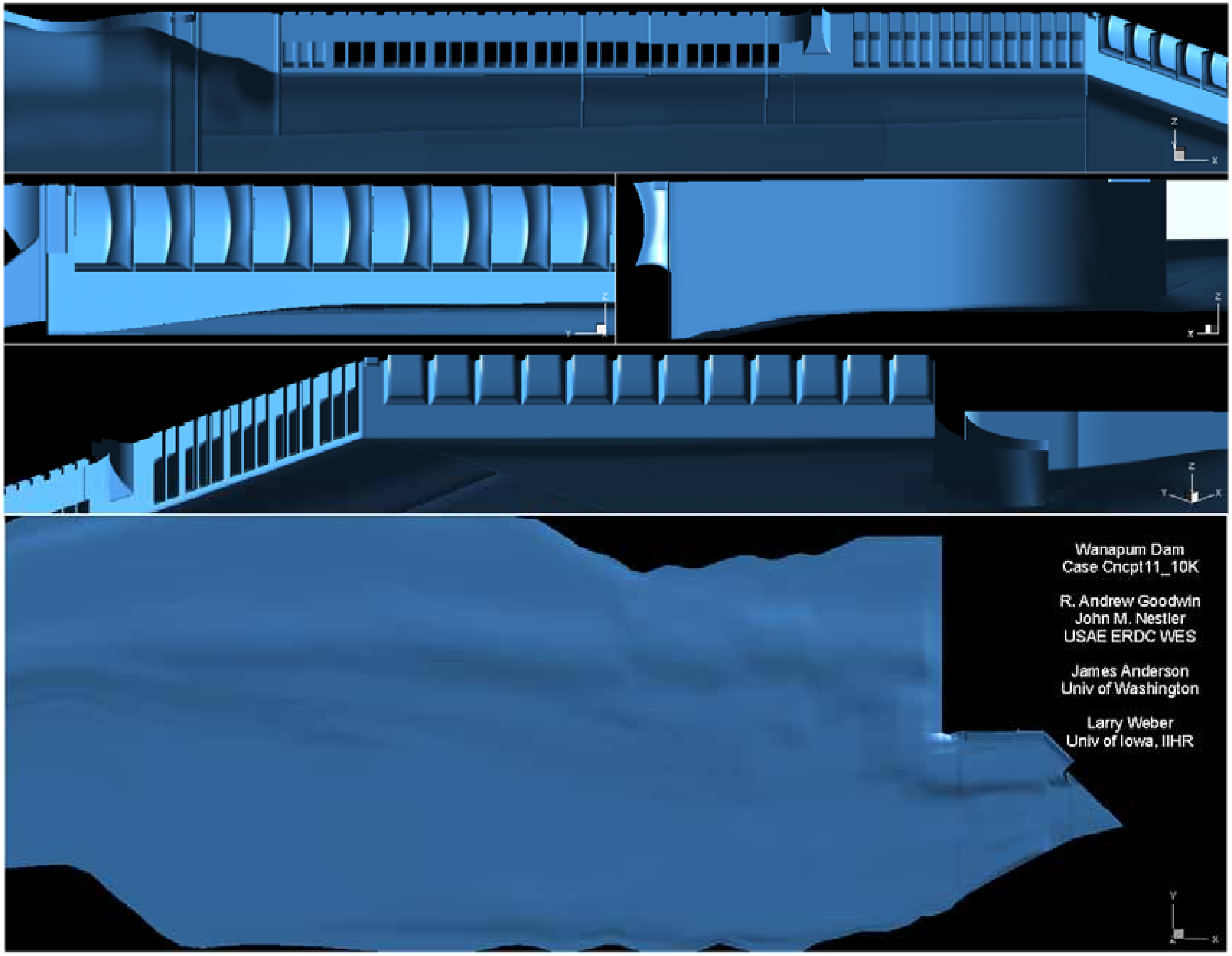
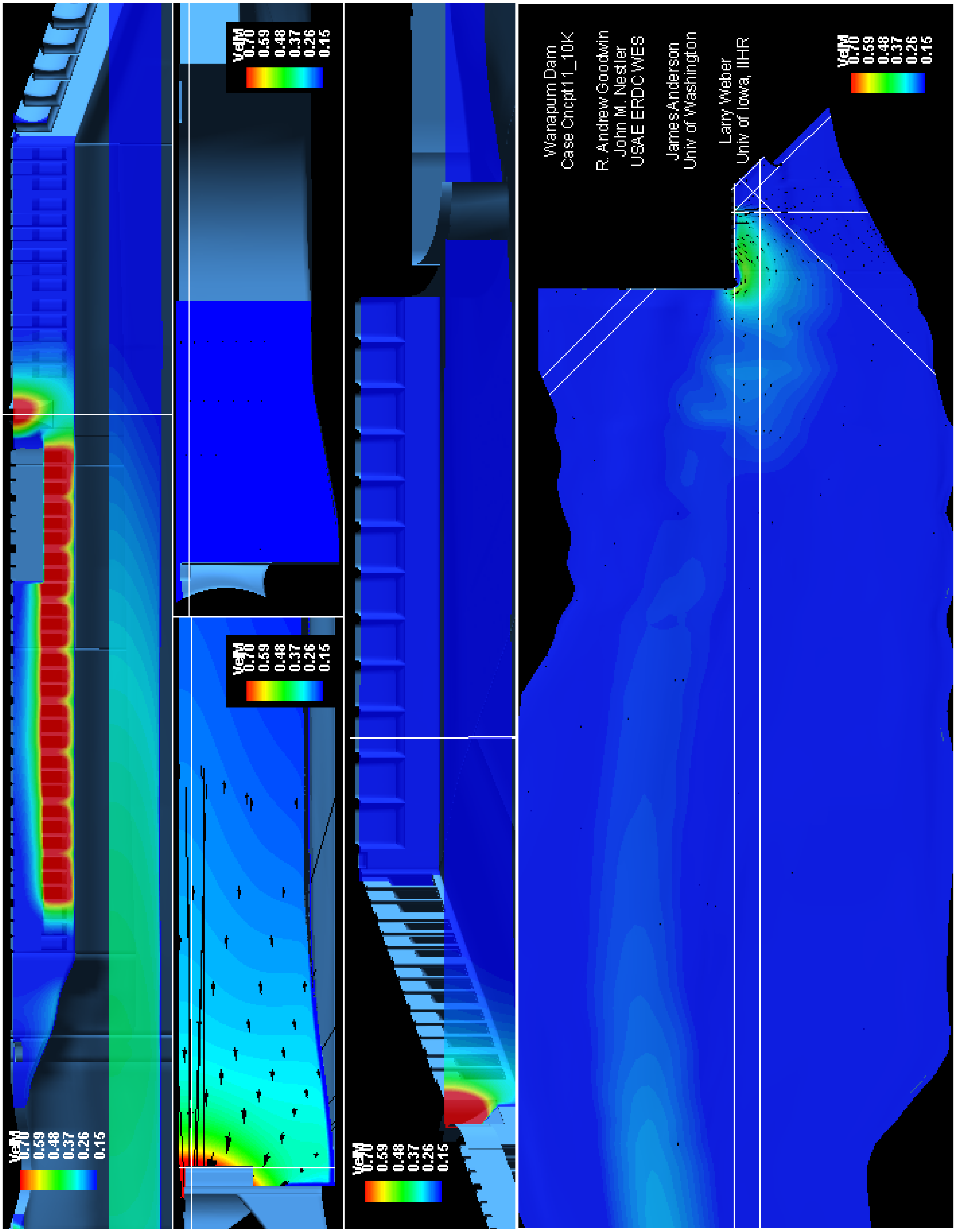


Figure A10. Wanapum Dam, Case Cncpt11_10K (Sheet 1 of 5)



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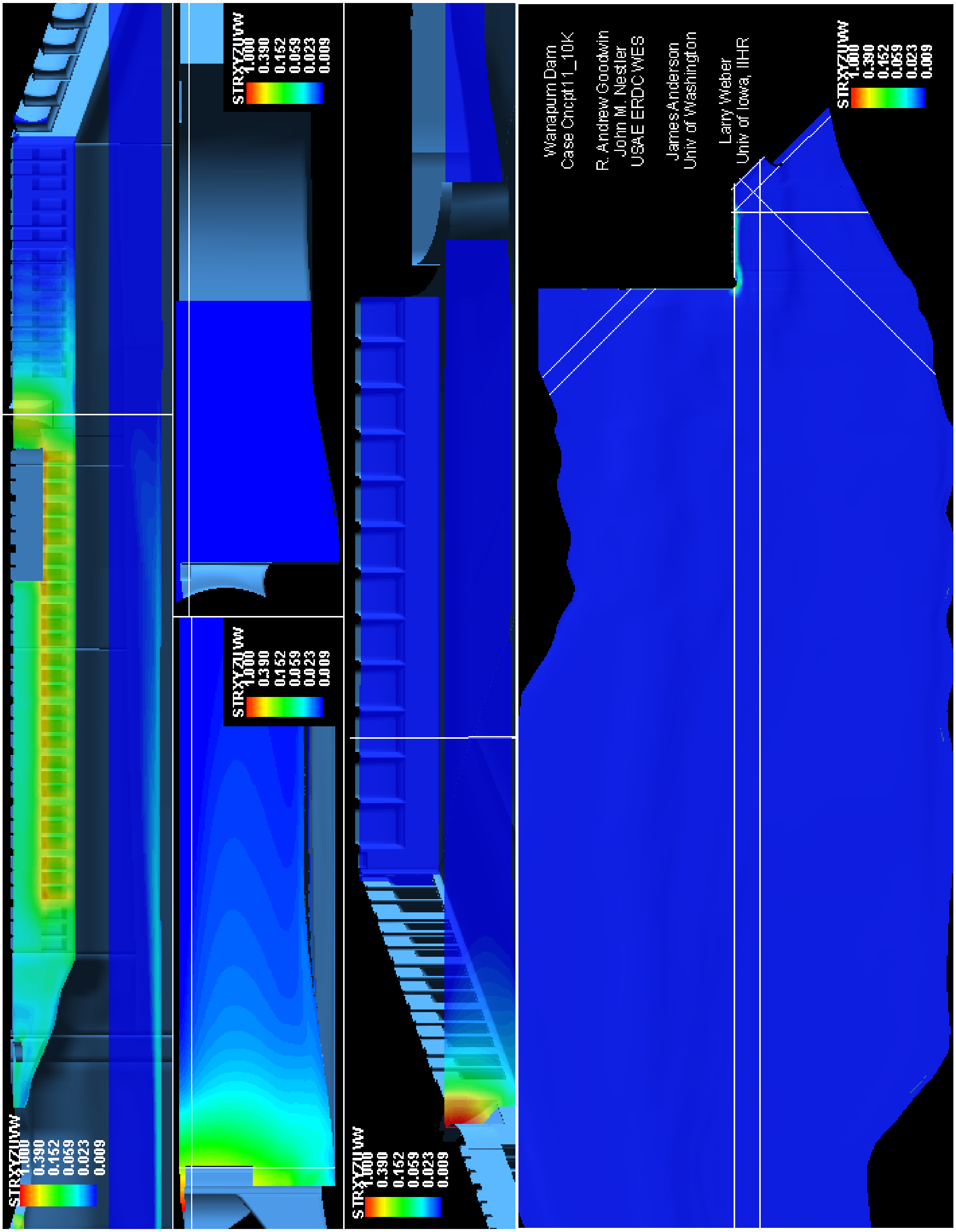

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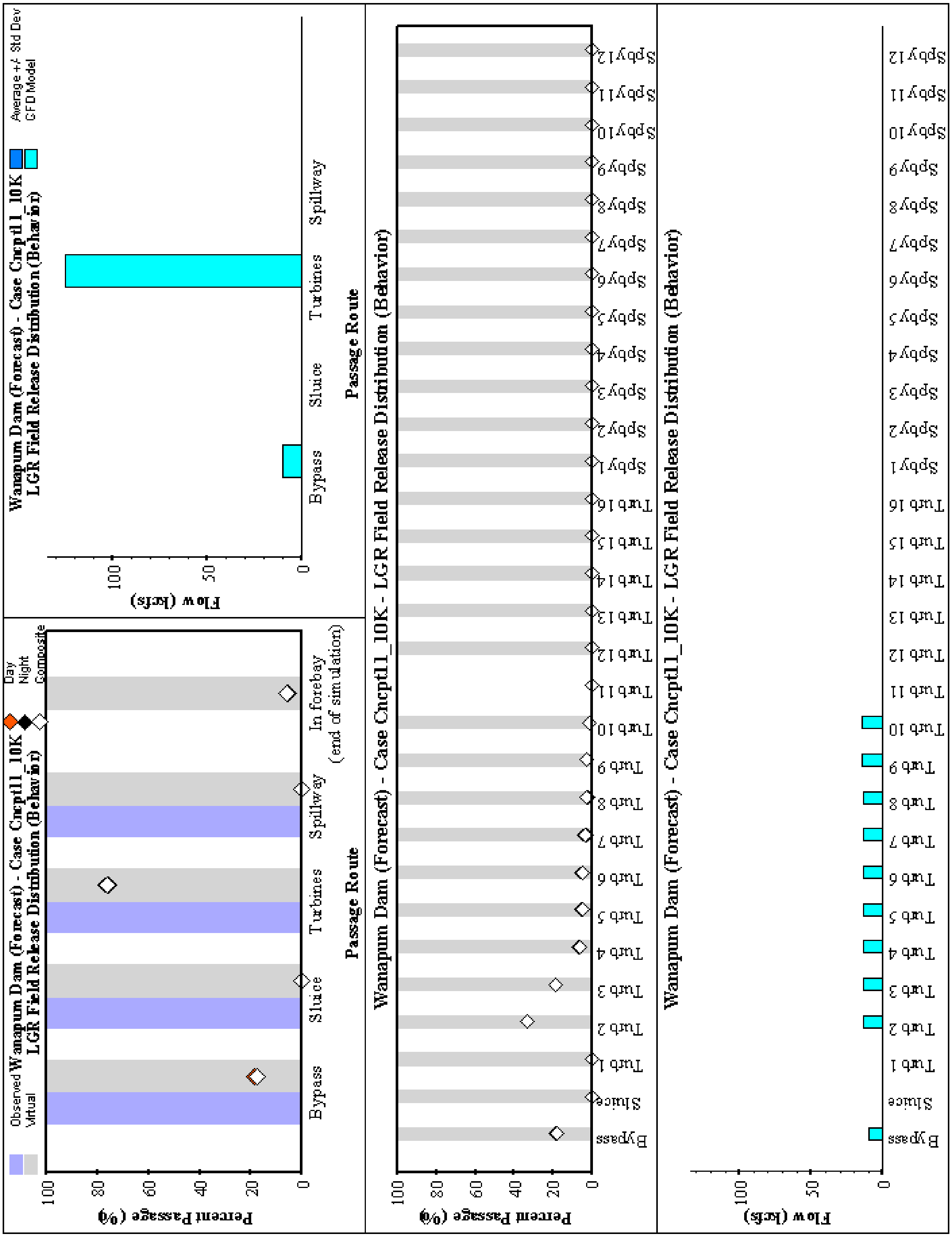

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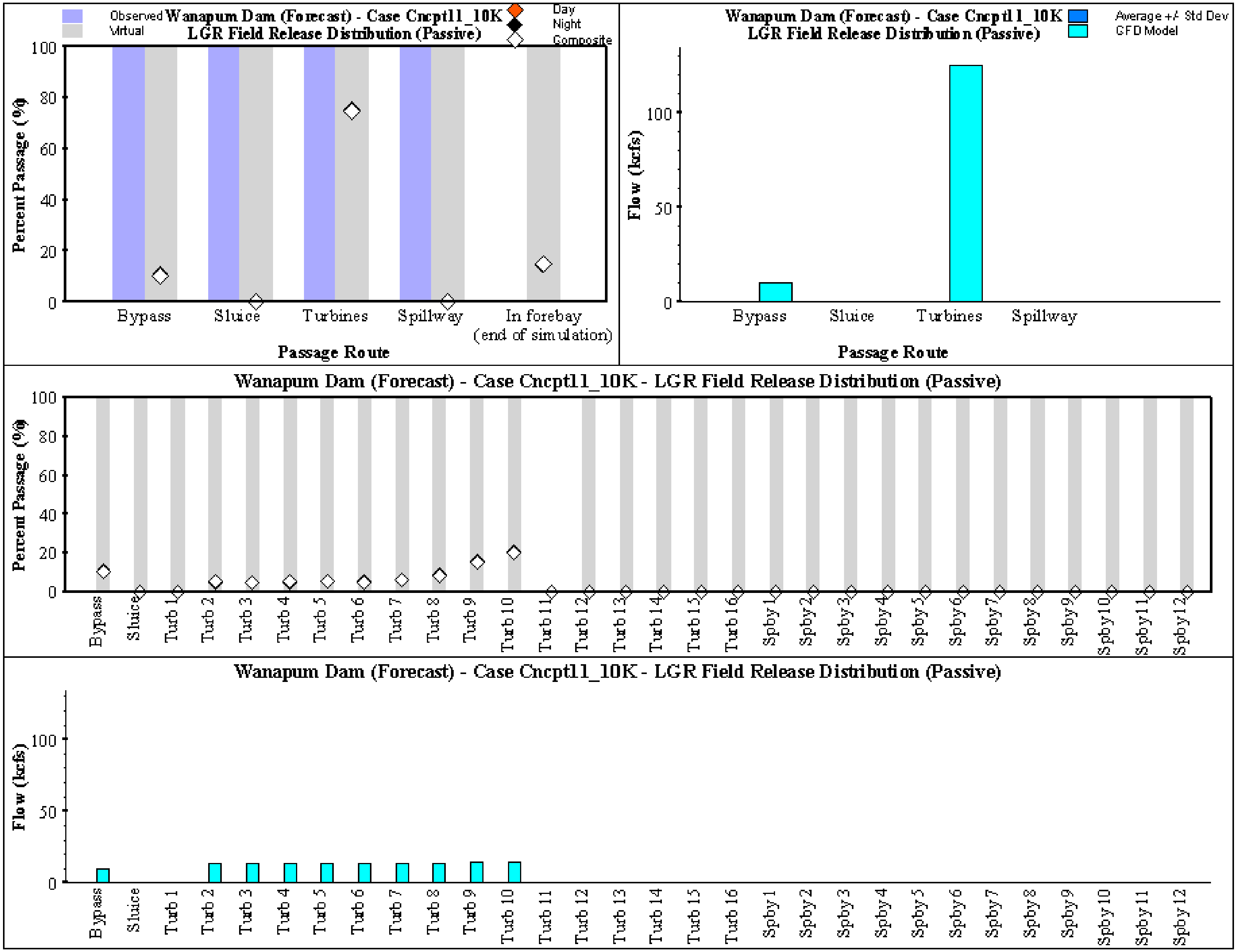

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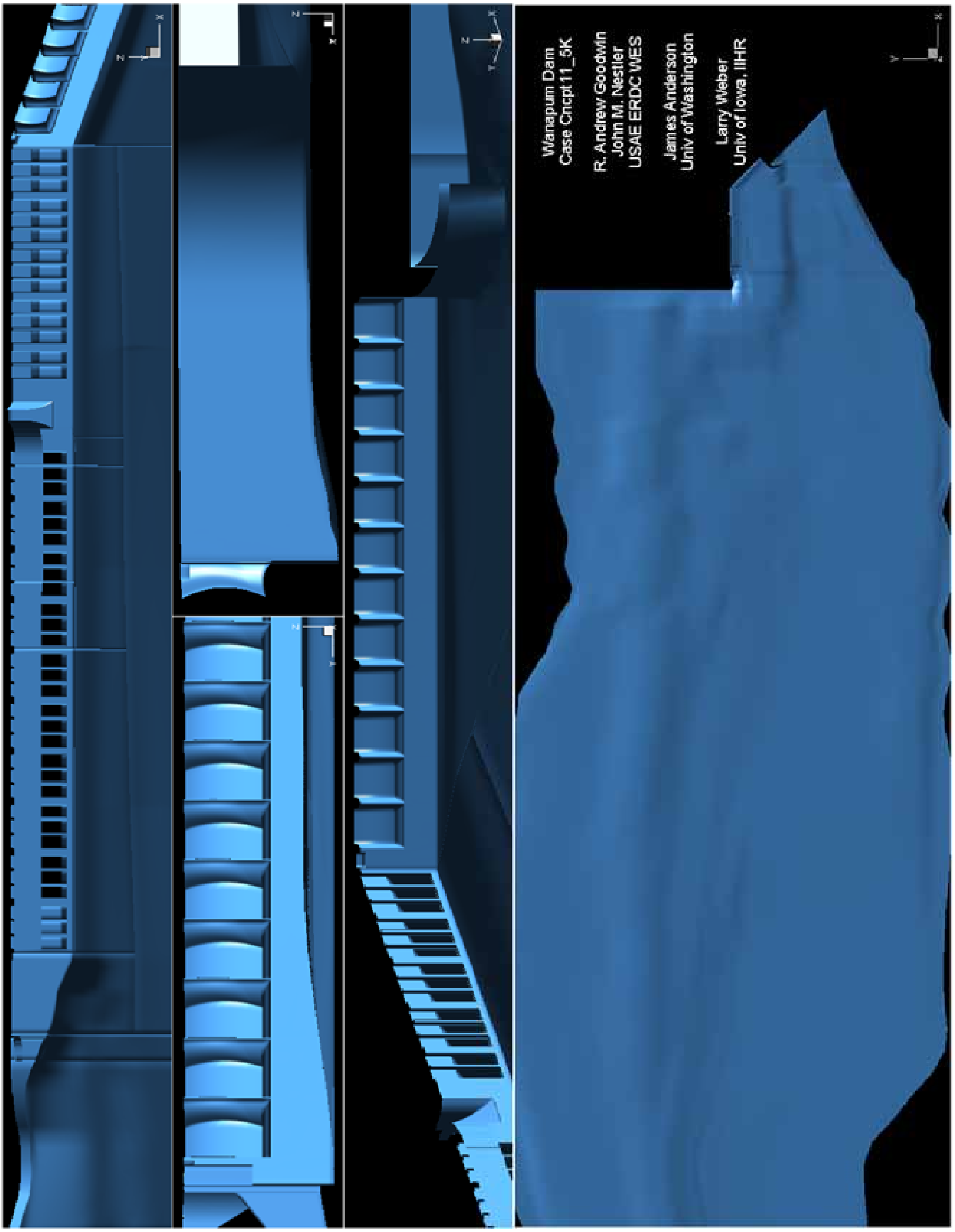
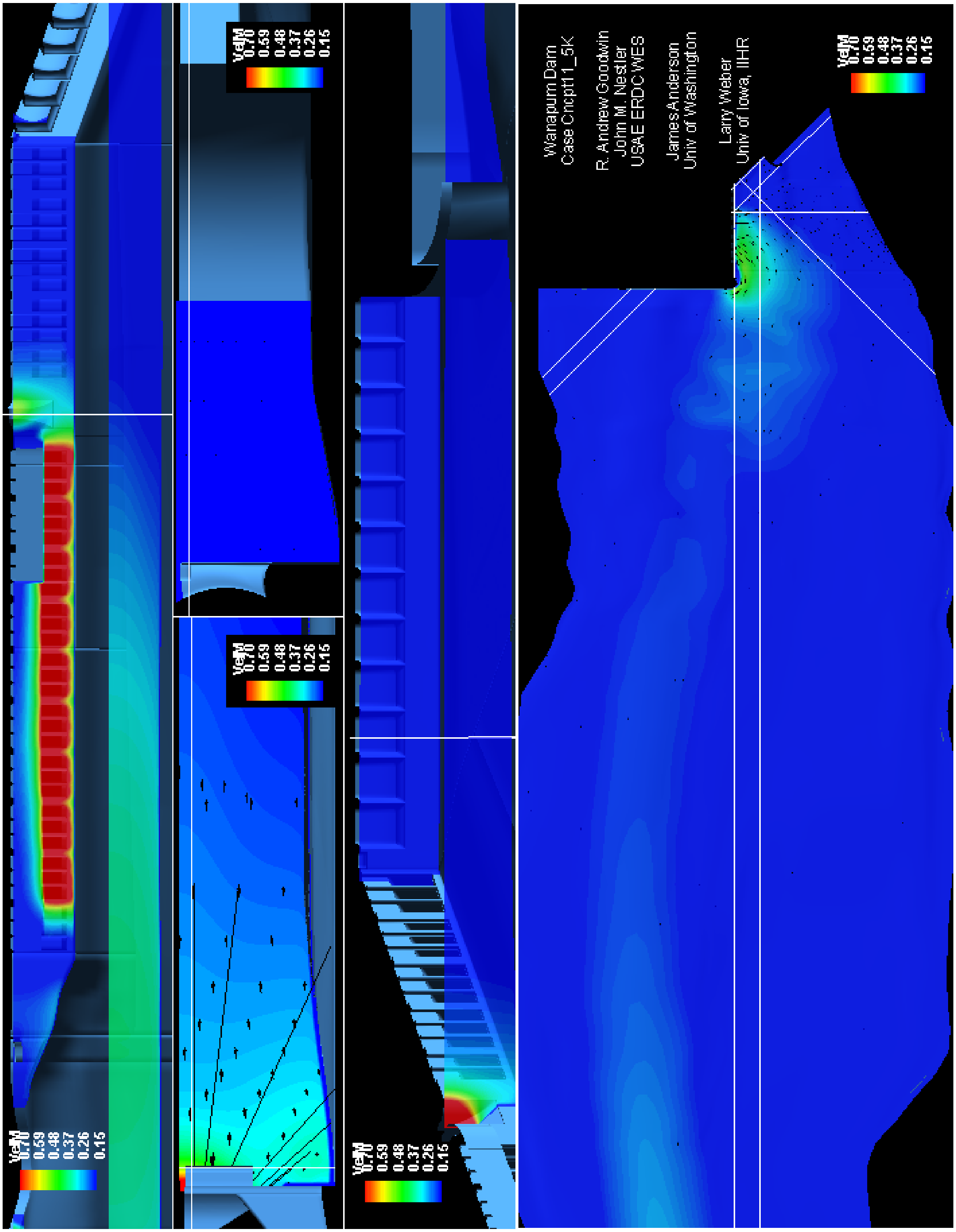


Figure A11. Wanapum Dam, Case Cncpt11_5K (Sheet 1 of 5)



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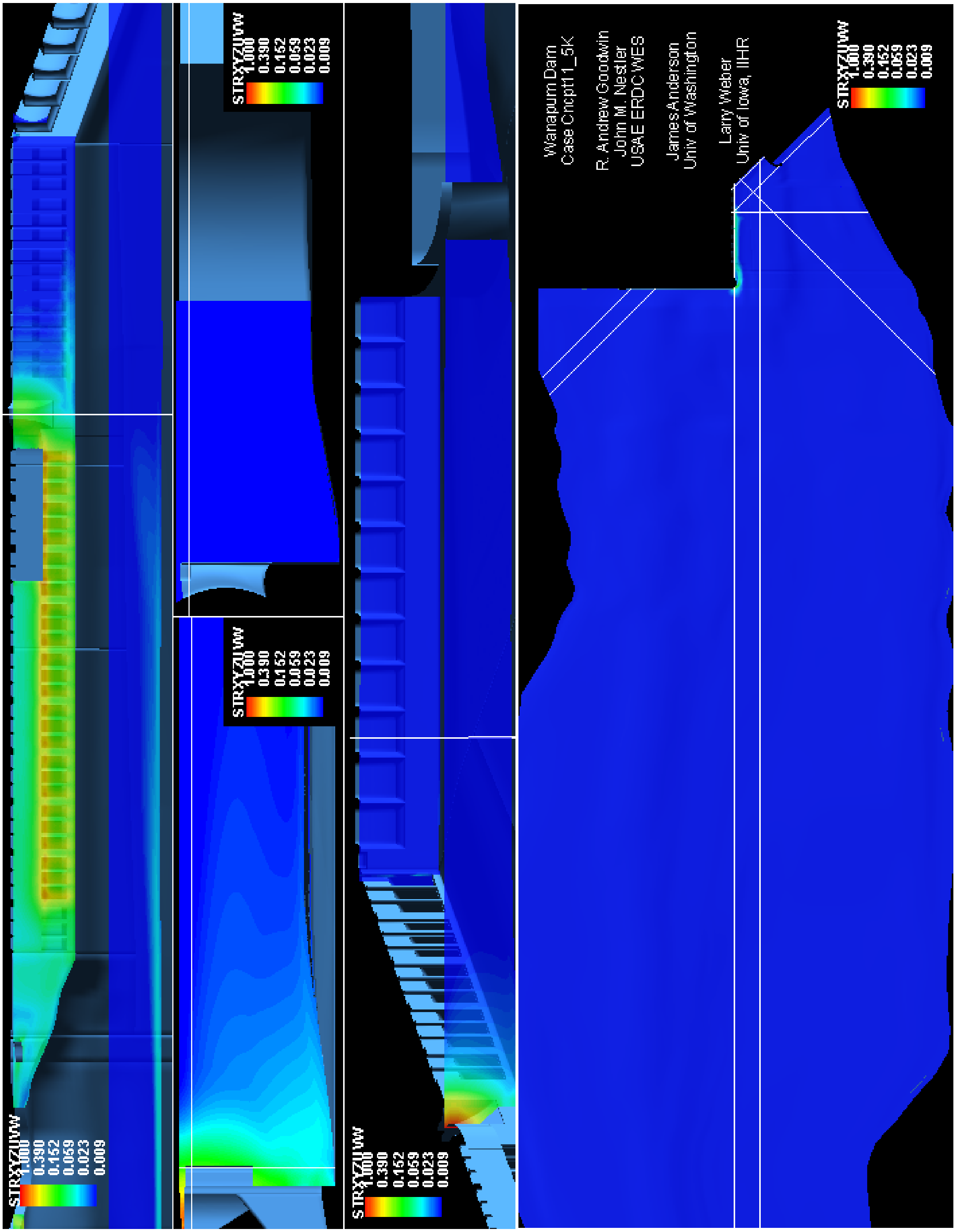

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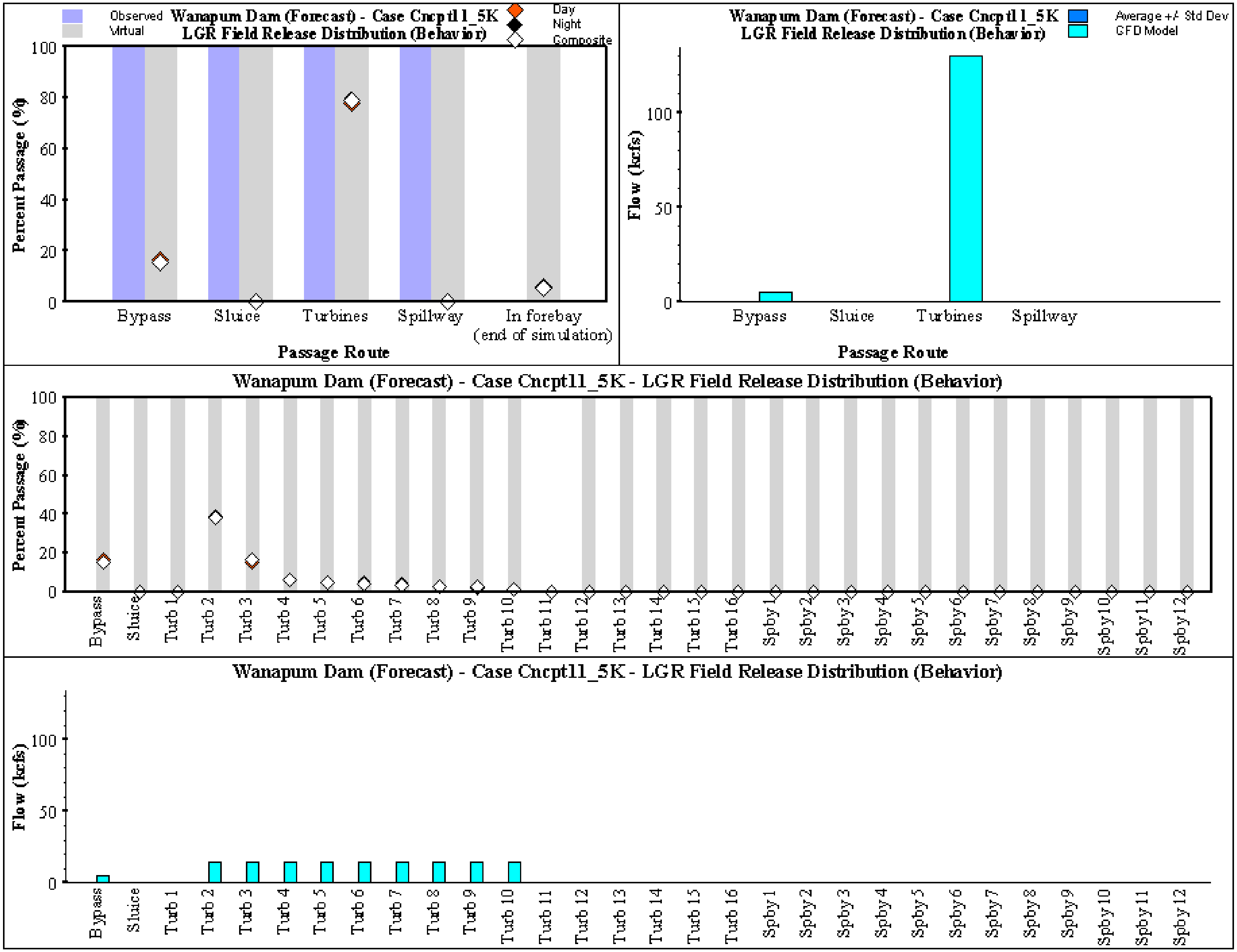

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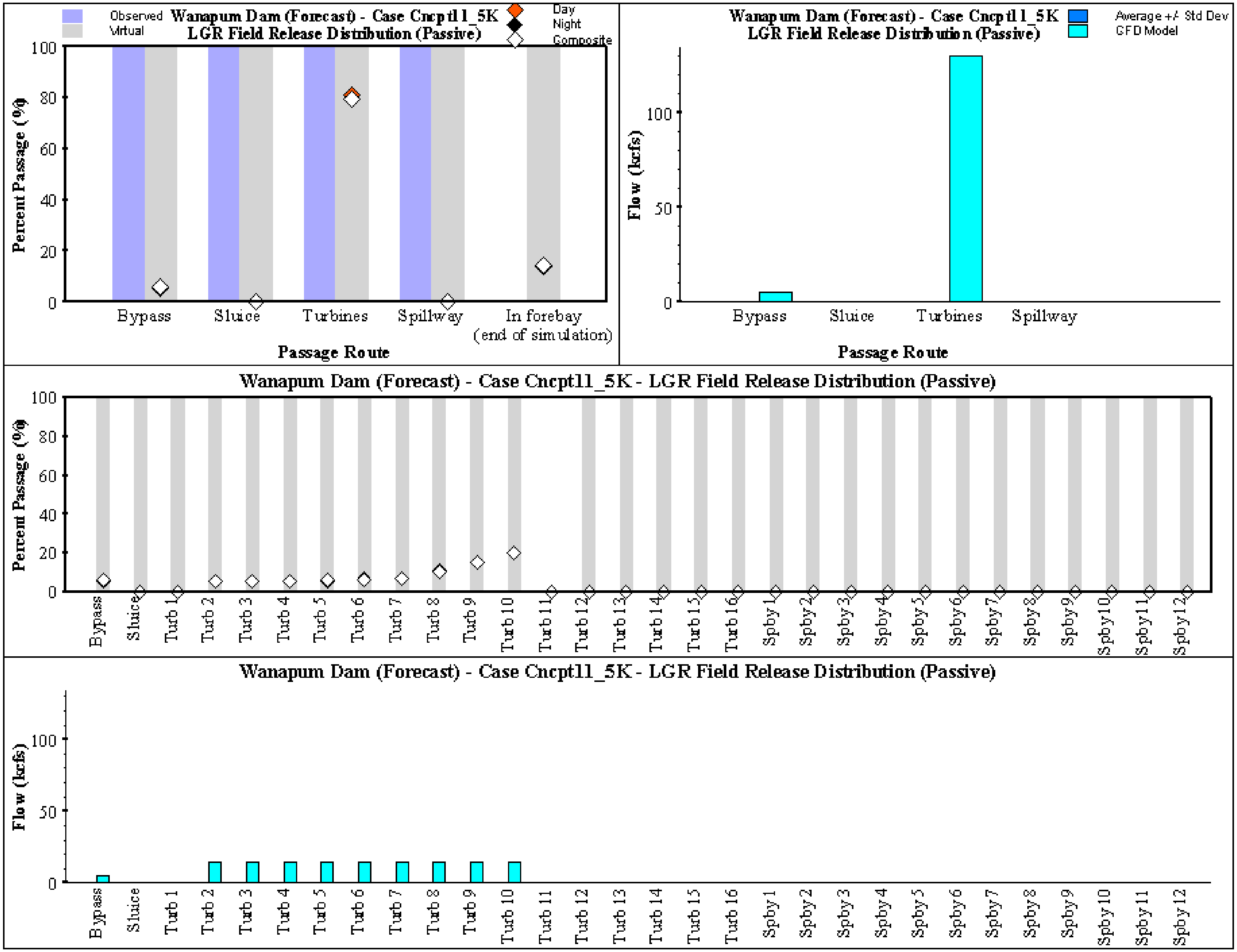

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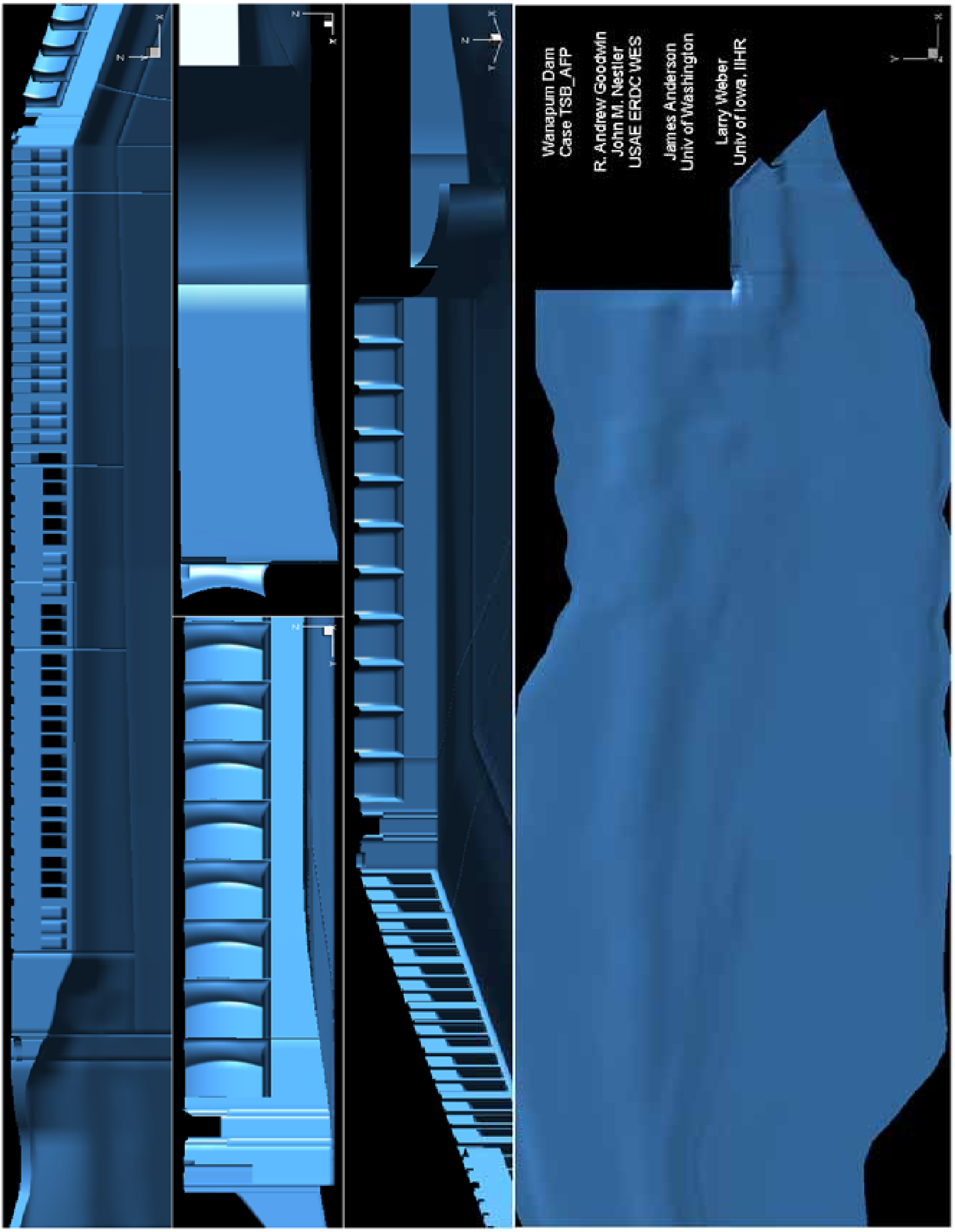
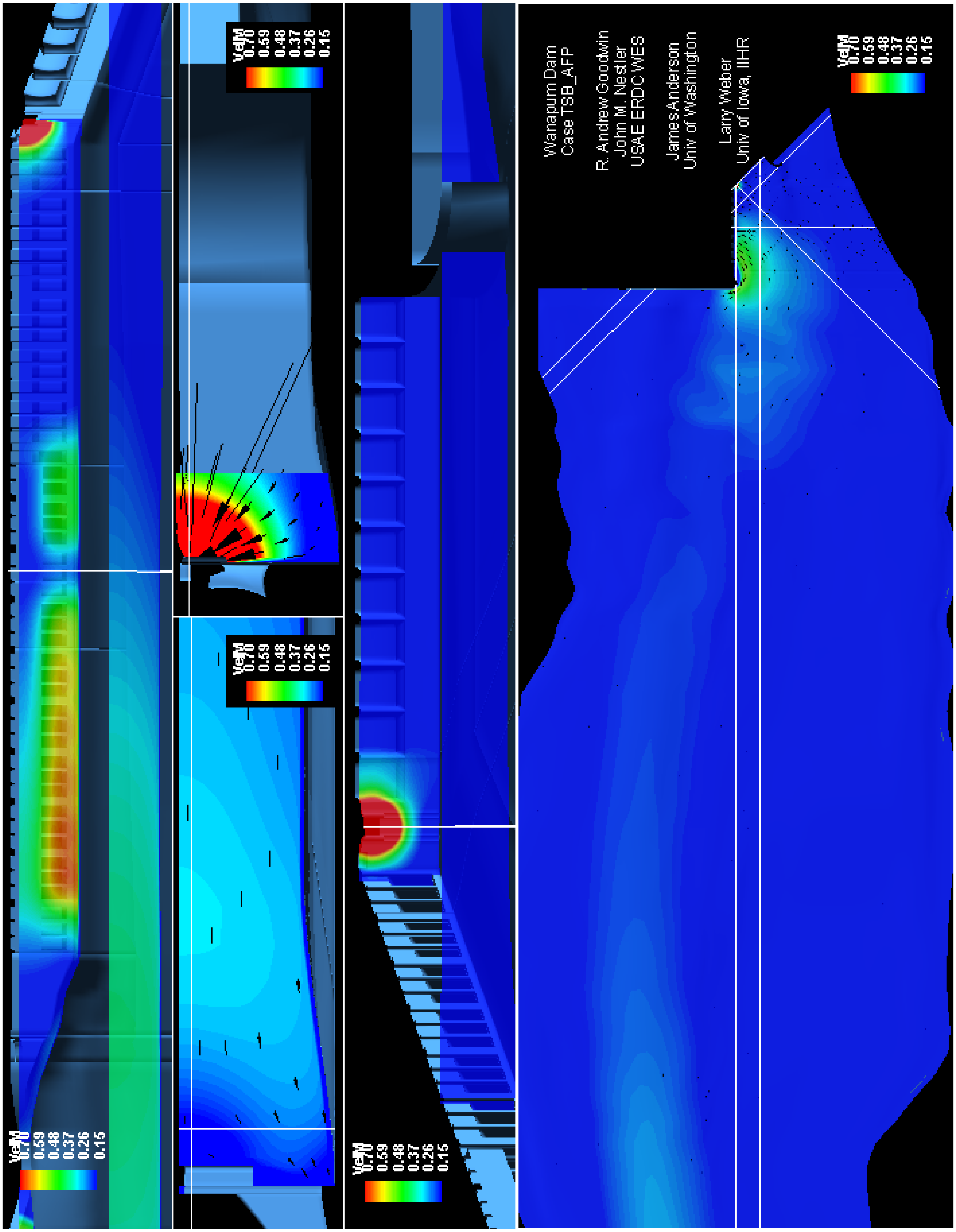


Figure A12. Wanapum Dam, Case TSB_AFP (Sheet 1 of 5)



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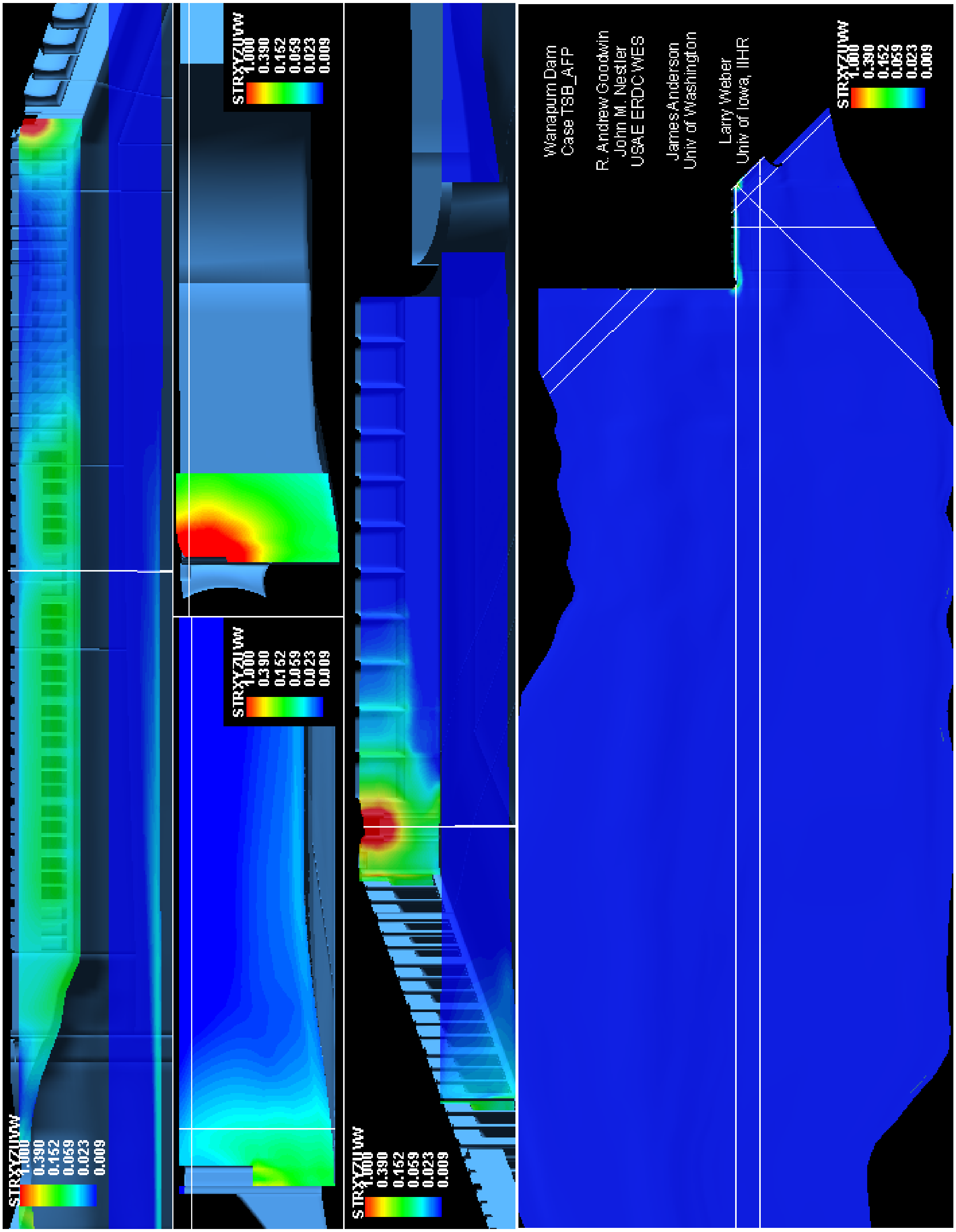

Figure A12. (Sheet 3 of 5)

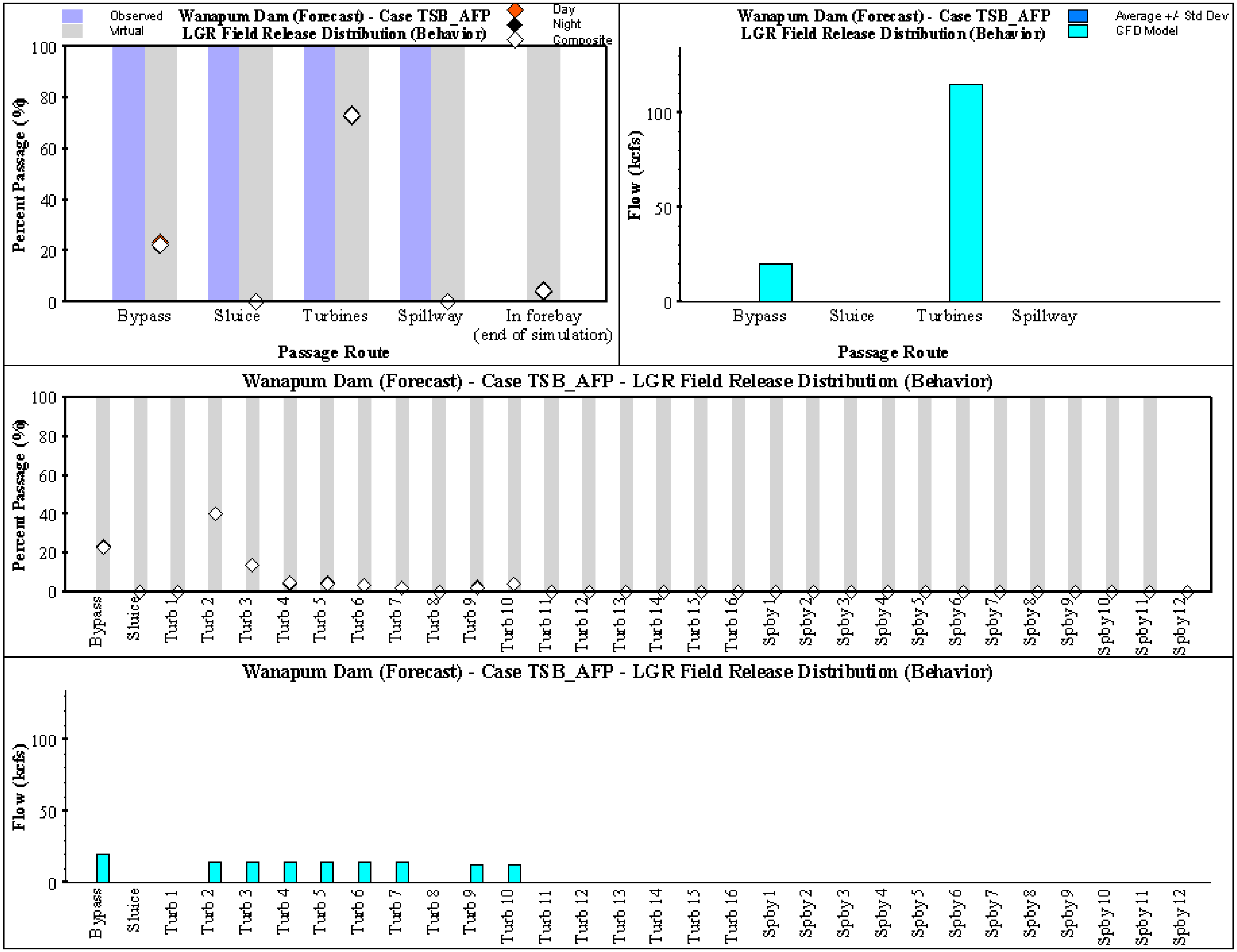

Figure A12. (Sheet 4 of 5)

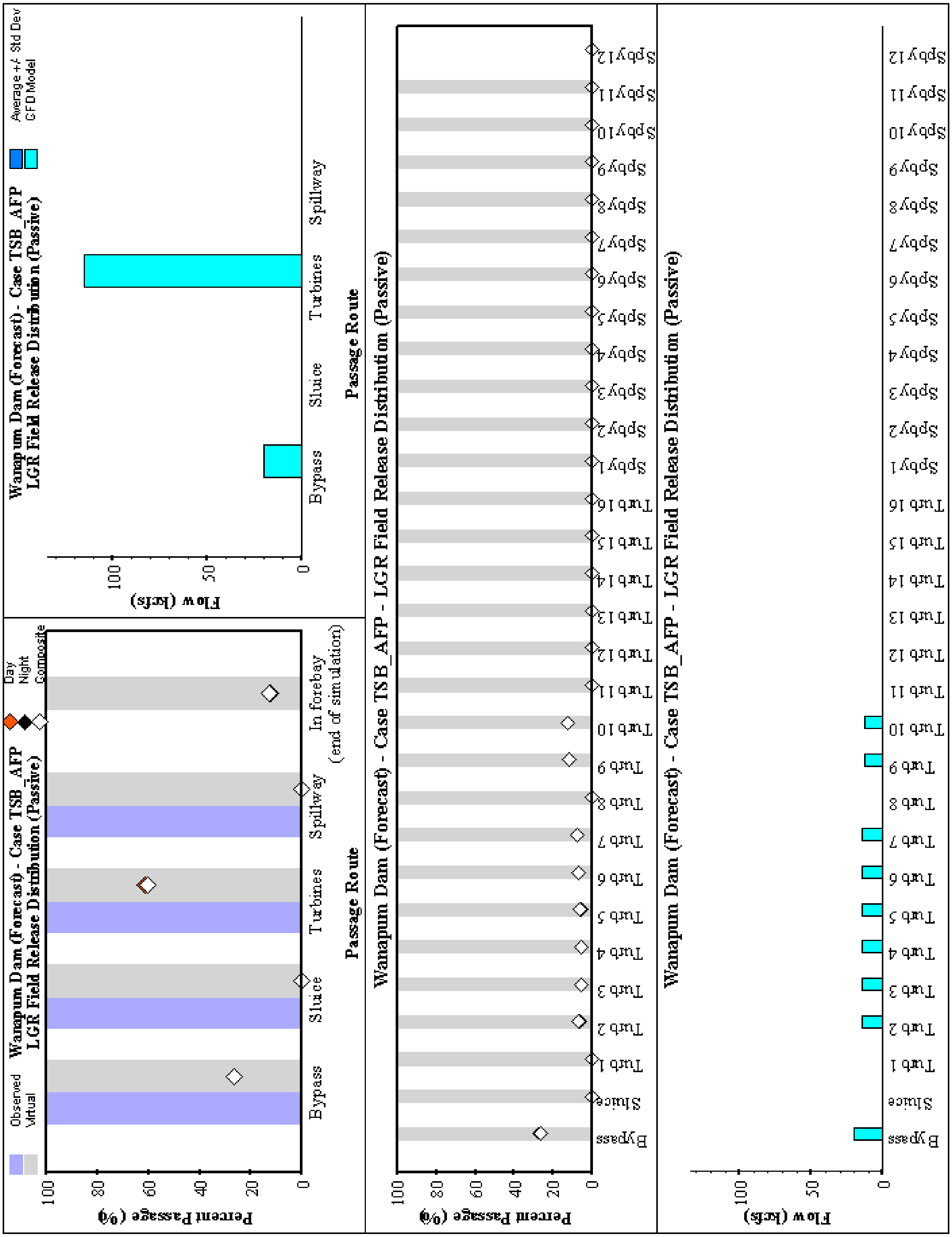

Figure A12. (Sheet 5 of 5)

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Evaluation of Wanapum Dam Bypass Configurations for Outmigrating Juvenile Salmon Using Virtual Fish: Numerical Fish Surrogate (NFS) Analysis

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R. Andrew Goodwin, John M. Nestler, James J. Anderson, Jina Kim, Toni Toney

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

As part of the Federal Energy Regulatory Commission (FERC) relicensing process, Public Utility District No. 2 of Grant County (the District) wishes to improve performance of fish bypass at Wanapum Dam. The Numerical Fish Surrogate (NFS) is a Eulerian-Lagrangian-agent model (ELAM) developed for analyzing, decoding, and forecasting the movement and passage behavior response of outmigrating juvenile salmon (migrants) in complex 3-D hydrodynamic fields near fish bypass systems in hydropower dam forebays. The NFS (and ELAMs, in general) uses a mechanistic "plug-and-play" behavior algorithm embodying a biological hypothesis of how an individual responds to biotic and/or abiotic stimuli.

The University of Iowa IIHR – Hydroscience and Engineering developed a computational fluid dynamics (CFD) model to describe the 3-D steady-state hydrodynamic fields associated with 12 different structural and operational fish bypass system configurations (cases) at Wanapum Dam. In Phase 1 of the study, forecast (virtual fish) and observed (radio-tagged fish) passage proportions were compared for five different cases from years 1997, 2001, and 2002. Comparison of forecast and observed passage for four out of the five cases were done blindly (i.e., independently reviewed and evaluated) and within the expected limits of about 5 to 10 percent for the bypass systems and considerably better than forecasts of passage from passive particles (i.e., behavior rules turned off). This indicates

(Continued)

15. SUBJECT TERMS

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Fish behavior
Fish passage
Individual-based models
Numerical fish surrogate
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U.S. Army Engineer Research and Development Center
333 SW 1st Avenue, Portland, OR 97208;
U.S. Army Engineer Research and Development Center
Environmental Laboratory
3909 Halls Ferry Road, Vicksburg, MS 39180-6199;
School of Aquatic and Fishery Sciences, Columbia Basin Research
University of Washington
1325 4th Avenue, Suite 1820, Seattle, WA 98101;
BAE Systems, Fisheries Engineering Team
40 S.E. Cascade Avenue, Stevenson, WA 98648

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migrant movement behavior in the flow field is likely an integral part of bypass success. In Phase 2 of the study, the NFS was used to forecast the passage response of migrants to seven different structural and operational design alternatives under consideration for Wanapum Dam prior to construction and installation.

Results indicate the NFS is a viable technology for use at Wanapum Dam to assess different fish bypass design alternatives. NFS performance is limited by (a) the robustness of the underlying mechanistic biological hypothesis, (b) accuracy and resolution of the CFD modeled hydrodynamics, and (c) accuracy and robustness of the observed (radio-tagged fish) passage proportions for describing the passage response of a target species or population. Concurrence between forecast and observed passage proportions supports the Strain-Velocity-Pressure (SVP) Hypothesis as an approximation of the strategy used by migrants to hydraulically navigate through complex flow fields. The NFS may be used to reduce uncertainty and, therefore, the cost and impact on migrants, in the process of designing and operating bypasses. NFS accuracy is expected to improve with additional observed data and model calibration.